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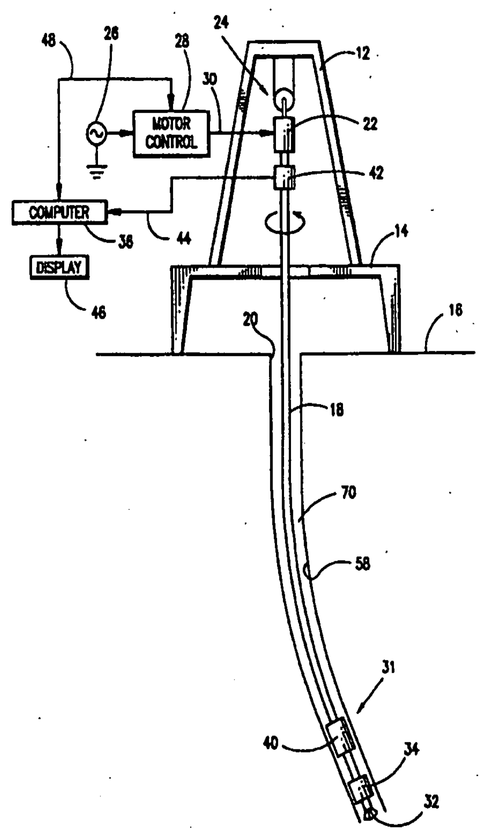
(54) Title: METHOD AND APPARATUS FOR DRILL STEM DATA TRANSMISSION

(57) Abstract

A drill stem communication system for transmitting data between downhole and uphole locations in a borehole includes at least one transducer (40, 40') at a first location on a drill stem (18) for modulating motion and/or stress in the drill stem (18), and at least one transducer (42') at a second location on the drill stem (18) for detecting the modulation. Control devices (36, 260, 312, 382) may be provided at both locations for establishing communication therebetween.



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METHOD AND APPARATUS FOR DRILL STEM DATA TRANSMISSION

Background of the Invention

This application claims the benefit of U.S. Provisional Application No. 60/062,214 of Arthur F. Kuckes, filed October 16, 1997, and entitled "Drill Stem Stress Modulation for Data Transmission", the disclosure of which is hereby incorporated herein by reference, and is a continuation-in-part of U.S. application no. 08/979,991, filed November 26, 1997, the disclosure of which is hereby incorporated herein by reference.

The present invention relates, in general, to data transmission in drilling systems of the type used in gas and oil well drilling and to the generation of electrical power downhole. More particularly, the invention relates to a method and apparatus for modulating the motion of a drill stem at one location on the stem and for detecting the modulation at a second location for establishing communication between the locations, and further to a method and apparatus for generating electrical power downhole and for supplying such power to downhole electronic equipment.

The need for better telemetry methods and apparatus for communicating data to downhole drilling equipment or uphole from such equipment is widely recognized. For example, there is a

need to send data representing desired drilling parameters such as desired borehole inclination, azimuth and tool face from a surface location to control equipment located downhole at the drill bit. Similarly, there is a need to send data representing drilling conditions, such as inclination and azimuth, etc., from downhole sensing and control equipment to the surface. Such data needs to be transmitted rapidly and accurately while the drill is in operation, in order to avoid unnecessary, time-consuming and expensive down time.

Conventionally, drilling of deep boreholes is carried out with a pressurized drilling fluid which can be used to drive drilling equipment at the bottom hole assembly and to carry away the debris produced by the drilling operation. The dominant method for borehole communication in use at the present time involves the generation of pressure pulses in the drilling fluid. For communication from a downhole location, pressure pulses are generated downhole in the drilling fluid, as by periodically interrupting the fluid flow, and the resulting pressure pulses are carried in the fluid and are detected at the surface. The most serious deficiency of such pressure pulse systems is their very slow data rate, which is limited to approximately one bit per second. Another deficiency is the inability of such systems to transmit data when underbalanced drilling fluids containing

gas bubbles are employed, for such bubbles absorb the pressure pulses before they reach the surface.

Electromagnetic systems have been developed in which drill string currents are generated and modulated, and these have a higher data rate than is possible with pressure pulse systems; however, these systems have a very limited range.

An additional problem encountered in downhole communication systems is the need for an adequate supply of electrical power downhole for operating sensing and control circuits and equipment, not only for operating a communication system, but for controlling the operation of the drill in response to received data. Batteries are unsatisfactory for this purpose because of their limited life, due in part to the adverse conditions at the bottom of a borehole. Fluid-driven turbines have been used to generate electrical power, but these require access to the fluid flowing inside the drill stem.

Thus, there is a need for an alternative source of electrical power for downhole operations which does not interface with fluid inside the drill stem. Further, there is a need for improved communication of sensed data and control information along a drill string between the surface and a downhole location in a borehole, and vice versa.

Summary of the Invention

The drill stem data communication system of the present invention has several aspects which may be utilized separately or in any combination to meet the particular needs of a borehole drilling situation. In general, the invention relates to a method and apparatus for transmitting data between locations along a drill stem. A first aspect of the invention is directed to the transmission of data from a downhole location along the drill stem to a surface location. In a second aspect, the invention is directed to the transmission of data from a surface location along the drill stem to a location in the borehole. A third aspect of the invention is directed to the transmission of data from a downhole location to a surface location, and then from the surface back to the downhole location to provide a feedback control of downhole equipment. A fourth aspect includes a method and apparatus for generating electrical power for the downhole electronic equipment which is used to receive and transmit data signals and for the equipment which operates the electronic controls for directional drilling in the borehole. In a preferred form of the invention, all these aspects are combined in a drilling control system.

Briefly, the present invention relates to a method and apparatus for modulating torsional or axial stress and/or motion in a drill stem for transmitting data uphole and downhole in a borehole being drilled. One embodiment the invention relates to

a method and apparatus for modulating torsional stress and/or rotation by varying the rate of rotation of a drill stem. The invention also relates, in another embodiment, to a method and apparatus for producing axial stress waves in the form of axial motion or of variations in tension or compression in a drill stem to transfer data. In still another embodiment, the invention relates to a method and apparatus for generating electrical power downhole and at the same time transmitting data in response to the rotation of the drill stem. To transmit data from one location to another along the drill stem, the motion of the drill stem is modified at one location, such as at a downhole location, to create motion or stress variations in accordance with the data that is to be transmitted, and sensors are provided at the other location, such as at the earth's surface, responsive to such variations to recreate the transmitted data for monitoring the downhole operation and for control purposes.

More particularly, a borehole communication system in accordance with one embodiment of the invention includes surface apparatus for generating data signals to be transmitted downhole. These signals are used to impose corresponding stress or motion variations on the drill stem, and a sensor at a second location along the drill stem, such as at the bottom hole assembly, responds to the stress or motion variations to produce corresponding data signals which are used at the second location

for control purposes. In a preferred form of the invention, the drill stem is rotated by a drive motor at the surface, and data signals are encoded and used to vary the rotational speed of the motor to impose torsional stress variations on the drill stem as its rate of rotation is modulated. The resulting changes in drill stem rotational speed can be detected at the downhole location and decoded for regulating the drilling operation. Alternatively, axially variable stresses can be applied to the drill string at the surface, as by raising or lowering the drill string in incremental timed steps to release pressure or tension in bursts either at the surface or downhole to produce axial stress pulses, or shock waves, which are detectable as motion or stress variations at a remote location. The stresses induced in the drill stem at a first location are detected by a sensor at the second location, which may be at a bottom hole assembly where conventional drilling control circuitry is located.

In the case where torsional drill stem stresses are caused by variations in the rotational speed of the drill stem, the sensor preferably includes accelerometers or apparent earth's field sensors. In another embodiment, the sensor may be an alternator coupled to the drill stem and driven by the stem rotation to produce an alternating output current having a frequency corresponding to the rate of rotation. Such an alternator may be incorporated in a drill stem stabilizer which

is fixed to the borehole wall at the downhole location. Such a stabilizer is illustrated, for example, in U.K. Patent No. 2,177,738B entitled "Control of Drilling Courses in the Drilling of Boreholes" wherein stabilizers are utilized for dynamic control of the bend of the drill string to control the direction of drilling.

When an alternator sensor is used, the alternator rotor, in the present invention, may consist of plural magnets located on the drill stem, with stator windings located in the stabilizer, which surrounds the drill stem. The rotation of the drill stem produces an AC current output from the stator windings, and this current is rectified to produce a direct current for powering downhole circuitry. Changes in the rate of rotation due to varying torsional stresses produced at the surface, for example in response to changes in the motor drive current, cause changes in the frequency of the output current from the downhole alternator, which changes can be detected and demodulated to produce data signals corresponding to the data being transmitted from the surface location. The data signals may then be used to provide instructions to the downhole equipment.

In another form of the invention, the rotation of a rotary drill stem can be modulated by turning the drive motor on and off in a pattern corresponding to the control signals to be

transmitted, and the on and off pattern is detected at the bottom of the drill hole to provide suitable control signals.

In still another embodiment of the invention, the communication system includes a data source downhole which is responsive to selected downhole parameters to produce data signals to be transmitted to a surface location. The data source may include sensors located at a drill collar, for example, to measure conditions of operation downhole and at the drill head and to produce corresponding output signals. These data signals are used to modulate the rotation of the drill stem, as by activating and deactivating a mechanical brake for applying a variable drag force to the drill stem to change its rate of rotation. This braking sends torsional stress waves along the drill stem, and such waves are sensed at the surface, as by strain gauges, accelerometers or the like. The surface sensor output is then demodulated to provide data signals at the surface location corresponding to the data signals produced downhole.

The foregoing torsional systems for modulating and launching stress waves and motion in the drill stem serve to encode digital information in the steel of the drill string. These waves travel along the drill string and are detected and processed to recover the encoded digital data. It is well known that torsional waves can be transmitted along a drill string, for in the past the performance of drill bits has been studied by noting at the

surface the time variation of torsional noise stresses generated by the drill bit during operation. Such noise stresses can be avoided while using the communication system of the present invention by removing the weight of the string from the drill bit while transmitting data. Alternatively, the torsional stress modulation used for the transmission of data can be carried out in a narrow band frequency channel where there is little noise from the operation of the drill bit. However, it has been found that under most conditions there is in fact relatively little drill bit noise transmitted to the drill stem because of the weight of the drilling collars, so there is relatively little interference with the communication system of the present invention from this source.

Axial stresses, which may include axial stress waves and axial motion, may also be used for drill string communication, in accordance with the present invention. In one form of the invention such stresses and motion are generated at the surface by raising and lowering the drill string. The stress waves are produced by prescribed incremental lifting or lowering steps and are detected at a bottom hole assembly at the downhole location by axial accelerometers. The output signals from the accelerometers are demodulated and twice integrated with respect to time to recover the encoded data from the surface.

Axial stress waves may also be produced downhole for use in transmitting data to the surface. For example, standard mud pulsing, which conventionally is detected at the surface by measuring pressure variations in the drilling fluid, can also be sensed uphole by detecting associated axial stress changes in the drill stem. This is effective, since the attenuation of axial stress in the steel pipe of the drill stem is significantly less than the attenuation produced by the drilling fluid, particularly at the higher frequencies desired for good data transmittal.

In another form of the invention, data relating to conditions and parameters of operation downhole and at the drill head are converted to electrical signals which are transmitted along the electrically conductive drill pipe to an axial stress pulse transducer located, for example, 100 meters above the sensors at the drill head. The transducer may be an hydraulic pressure modulator which is controlled by the encoded data signals to mechanically produce stress pulses in the drill stem. These pulses can be in the form of axial motion imposed on the stem or axial stress imposed on the stem, to produce variations in tension or compression. Such variations travel along the drill stem and are sensed at the surface. The transducer preferably includes a pressure chamber and a release chamber, both containing hydraulic fluid. Downward pressure of the drill stem during drilling causes fluid to flow into the pressure

chamber from the release chamber. To effect communication, the drill stem is lifted, causing the lower 100 meters of the stem to be supported by the transducer and thus to exert a force which pressurizes the hydraulic fluid in the pressure chamber. This fluid can then be released from the pressure chamber in incremental bursts by a solenoid valve under the control of encoded data signals. Each time the valve is opened, the weight of the 100 meter long drill stem below the transducer causes the stem to drop a distance corresponding to the amount of fluid released by the valve. When the valve is closed, the motion of the stem is halted. The release of the 100 meter section of drill stem reduces the tension in the portion of the drill stem above the transducer, and closing the valve restores the tension. This produces axial shock waves, or stress pulses in the upper part of the drill stem which travel up the drill stem to the surface. A suitable sensor such as a strain gauge is located on the drill stem at the surface to measure received axial shock waves and the resulting stress signals are then demodulated to reproduce the downhole data signals at the surface.

In a variation of the foregoing, the hydraulic pressure chamber in the transducer may be primed by a fluid pump, rather than by the weight of the drill stem.

In another aspect of the invention, data to be transmitted downhole is encoded at the surface, and is used to control a

surface hydraulic transducer which generates axial stress or shock waves for transmission downhole. In one form of this aspect of the invention, a hydraulic pump is operable to pump hydraulic fluid into a pressure chamber at or near the earth's surface. The weight of the drill stem and drill head is carried by the hydraulic fluid in this chamber, thereby placing the fluid under high pressure. A solenoid valve controlled by the encoded data is operated to release hydraulic fluid from the pressure chamber in incremental steps or bursts, each of which serves to drop the drill stem a short distance to produce corresponding axial shock waves, or pressure pulses. These shock waves travel along the length of the drill stem in an axial direction and are detected by accelerometers or by strain gauges located near the bottom of the borehole. The variations in stress so detected are converted to electrical signals which are demodulated to produce corresponding data control signals at the downhole location.

In accordance with the invention, therefore, data communication in a borehole is carried out by variations in drill stem rotation, by axial stress waves generated at the surface, by axial stress waves generated downhole, or by a combination of these techniques.

Data transmission between the surface and the downhole location is preceded by a suitable command sent from the surface to signal the downhole electronics to start a data transmission,

or to prepare to receive a data transmission. Thus, for example, a specific sequence of starting and stopping of the fluid pumps and/or drill stem rotation can be used, or a sequence of lifting or lowering the drill stem can be used. The sequence is specific to the encoded command, and after the command is given, transmission of encoded data begins.

The system of the present invention is particularly well suited to the establishment of communication links along the drill stem in the controlled rotary drilling of directional holes, not only because torsional or axial stress can easily be induced, but because the rotation of the drill stem can be used as a source of power for the control circuitry downhole.

Detailed Description of Drawings

The foregoing, and additional objects, features and advantages of the present invention will be more clearly understood by those of skill in the art from the following detailed description of preferred embodiments thereof, taken with the accompanying drawings, in which:

Fig. 1 is a diagrammatic illustration of a rotary drilling system for oil/gas wells, incorporating a downhole stress modulator and a surface detector unit for data transmission in accordance with the present invention;

Fig. 2 is a diagrammatic illustration of an hydraulically controlled drill stem stabilizer brake for producing torsion modulation for the system of Fig. 1;

Fig. 3 is a cross-sectional illustration of an MWD drill string control unit with an hydraulic controller for the drill stem torsion modulator of Fig. 2, and further illustrating the provision of a downhole alternator;

Fig. 4 is a cross-sectional illustration of a second embodiment of a torsional stress modulator for use in the system of Fig. 1, utilizing inertial stress modulation;

Fig. 5 is a cross-sectional view taken along line A-A of Fig. 4, showing a brake for producing stress modulation;

Fig. 6 is a cross-sectional illustration of a surface detector unit for the system of Fig. 1;

Fig. 7 is a diagrammatic illustration of an alternative surface detector unit;

Fig. 8 is a diagrammatic illustration of another embodiment of the invention, incorporating a surface axial stress modulator and a downhole sensor; and

Fig. 9 is a cross-sectional diagrammatic view of downhole electronics for an axial stress detector;

Fig.10 is a cross-sectional view of a first embodiment of a downhole stress wave transducer for use in the system of Fig.1;

Fig.11 is a cross-sectional view of a second embodiment of a downhole stress wave transducer;

Fig. 12 is a cross-sectional view of a fluid pump for supplying hydraulic fluid to the stress wave transducer of the invention; and

Fig. 13 is a cross-sectional view of a surface stress wave transducer.

Detailed Description of Preferred Embodiments:

Turning now to a more detailed description of the present invention, there is illustrated in Fig. 1 a rotary deep well directional drilling system 10 for drilling oil or gas wells. The drilling system includes, for example, a drilling derrick 12 mounted on a drill platform 14 located on the earth's surface 16. The derrick supports a drill string 18 which extends into a borehole 20 in the earth, the drill string being supported by a top drive motor 22 secured to the derrick 12 by a suitable cable and elevator lifting mechanism generally indicated at 24. The top drive motor 22 receives power from an alternating current source 26 through a motor control circuit 28 by way of line 30, as is conventional in the petroleum industry. The drill string 18 includes, at its distal end, a bottom hole assembly (BHA) 31, which includes a drill bit 32 driven by rotation of the drill stem 18 by the motor 22 to produce the borehole 20. Carried by

the drill stem near the drill bit 32 is a measurement while drilling (MWD) control unit 34 for use in providing control signals for operation of the drill bit, and for producing data relating to borehole inclination and azimuth, as well as other parameters, such data being collected for transmission to the surface for use in monitoring and controlling the operation of the drill bit.

To provide communication between the MWD controller 34 and surface equipment such as a computer 36 or other control equipment, the present invention provides a drill stem stress modulator 40 in a downhole location near the control unit 34. The drill stem stress modulator 40 generates either axial or torsional stress waves on the drill stem in response to data signals produced by the control unit. The modulator 40 may consist of any desired mechanism for generating torsional or axial stress waves on the drill stem corresponding to the data which is to be transmitted to an uphole location.

A suitable surface detector 42 may be in the form of a strain gauge or an accelerometer, for example, which produces corresponding output signals on line 44 representing the data signals generated at the modulator 40. These output signals are supplied to the computer 36 which processes the data in a well-known manner to provide outputs to a display 46 and/or by way of line 48 to the motor controller 28 for regulating the operation

of the rotating drill string 18. As described above, since the axial or torsional waves produced the modulator 40 can be transmitted accurately along the drill stem 18, data signals from the control unit 34 can be rapidly and accurately communicated to the surface.

Examples of the torsional stress modulator 40 and the drill string control unit 34 are illustrated in Figs. 2 and 3, respectively, to which reference is now made. The torsional stress modulator 40 in one embodiment is a hydraulically-actuated brake which includes a spiral fin stabilizer body 50 of conventional design fabricated as a part of a drill stem section 52 connected into the drill stem 18. The stabilizer 40 is shown above the control unit 34, and is of conventional design, incorporating, for example, 18 hydraulically-activated pistons 54 located in spiral fins 55. In an exemplary brake modulator, each spiral fin may carry six hydraulically-actuated piston buttons, each 1.75 inches in diameter. A stabilizer with such a configuration is marketed as an adjustable stabilizer for drill stem stiffness control by Andergauge Drilling Systems. The pistons, when activated, engage the side wall of borehole 20 and serve to position the stabilizer body 50 with respect to the borehole.

In the present invention, an external hydraulic line 56 is connected to direct pressurized drilling fluid into the cylinders

in which the pistons 54 are mounted. The drilling fluid expands the pistons against the wall of the borehole 20, with the pistons being dimensioned to produce a significant drag on the borehole wall when they are activated. By regulating the flow of drilling fluid in the hydraulic line 56, the pistons are expanded and contracted to cause the pistons to brake or release the drill stem and thus cause variable torsional stresses in the drill string. This braking action produces torsional waves in the drill stem 18 which can be detected at the surface detector 42.

As illustrated in Fig. 3, the hydraulic line 56 is connected to an electronically controllable hydraulic valve 60 located in the drill string control unit 34 which is incorporated in a drill stem segment 62 connected below the modulator 40 but above the drill bit 32. High pressure drilling fluid is supplied from the surface and flows downwardly through the drill stem core 64, flowing through both the drill string segment 52 illustrated in Fig. 2 and the segment 62 illustrated in Fig. 3, and thence to the drill bit 32, in conventional manner. In accordance with the present invention, however, a small portion of the high pressure drilling fluid is supplied from the core 64 through an inlet 66 and through the hydraulic valve 60 to the hydraulic line 56, with excess fluid being bled through outlet 68 to the exterior of the drill string segment 62 for return to the surface through the drill string annulus 70.

The hydraulic valve 60 is mounted in an MWD electronics cavity 72 within the segment 62. Also included in the cavity, in conventional manner, is a battery pack 74 connected to a sensor module 76 which may include accelerometers, magnetometers, and the like. The sensor module 76 is connected to a control electronics module 78 which produces output signals on line 80 for controlling the hydraulic valve 60.

The hydraulic control valve 60 is similar in design to those found in conventional MWD fluid pulse modulator systems which are used to generate fluid pressure pulses. However, in the present invention, the hydraulic valve 60 is used to produce hydraulic fluid in line 56 under pressure to operate the pistons 54, as discussed above, to produce a torsional braking effect rather than to produce pressure pulses in the fluid flowing in core 64 or in the borehole 70.

The control electronics module 78 includes circuitry responsive to the sensors in module 76 to produce output data signals corresponding to acceleration values, magnetic field, gravity measurements, or any other desired parameter, the control electronics converting the detected parameters into data signals which are encoded and used to activate the hydraulic valve 60. The opening and closing of valve 60 under the control of the data signals produces variations in the hydraulic pressure in line 56 to activate and deactivate the pistons in modulator 40 to thereby

produce torsional stress modulation, or stress waves, in the drill string for detection at the surface. The surface sensor 42 detects the stress waves and produces corresponding signals on line 44 which are delivered to computer 36, where the data is utilized in conventional manner to obtain measurement of conditions in the borehole and to control the operation of the drill, among other things. Although the control electronics module 78 is illustrated as controlling only the hydraulic valve 60, it will be understood that the signals may also be used to provide steering signals to the drill bit 32, and may be used for various other purposes as is known in the art.

Not only are the stress waves produced in the drill stem by modulator 40 measurable at the surface, but they are also measurable by the MWD sensors 76 to provide feedback signals to the control electronics 78. These feedback signals enable the control electronics to regulate the hydraulic control valve 60 to adjust the amplitude of the stresses induced by the modulator 40.

The drill system MWD control unit 34 diagrammatically illustrated in Fig. 3 is of conventional design, and because it is adapted to rotary drilling systems it readily receives communication from the surface. Such communication may be provided by varying the drill stem rotary speed in a programmed manner, with the changes in RPM of the stem being detected by the accelerometers or magnetometers in the downhole sensors 76. The

downhole sensors then produce control data signals for the control electronics 78 to enable the operator of the drill system at the surface to control the operation of the MWD control unit. It should also be noted that although the control unit is shown as being powered by a battery pack, the power for the control unit can be supplied by other conventional sources, such as by a fluid-driven turbine alternator in the drilling fluid flow stream.

The torsional stress modulator 40 described above and illustrated in Fig. 2 requires contact between the pistons 54 and the borehole wall to produce the required the stress waves. However, such contact between the drill stem and the borehole wall may not always be reliably available, and accordingly an alternative form of the modulator is illustrated in Fig. 4 by an inertial modulator 90. This modulator consists of a large annular mass 92 mounted for rotation about a drill stem segment 94. The mass 92 is mounted on a set of bearings (not shown) to allow free rotation of the mass about the drill stem segment 94. As before, high pressure, high velocity drilling fluid, indicated by arrow 96, flows through a central passageway 98 in the drill stem segment and, after flowing through and around the drill bit, flows upwardly around the drill stem in the annular space 70 in conventional manner. The average motion of the mass 92 is governed by friction between it and the fluid 96 flowing upwardly

in the borehole and by the proximity of the exterior surface of the mass to the borehole wall. The mass 92, which may have a weight of about 1000 pounds, will tend to remain stationary as the drill stem is rotated so that modulation of the torsion in drill stem 18 can be accomplished by a brake mechanism, indicated at 100 in Fig. 4, operating between the mass 92 and the drill stem segment 94, as will be described below.

A preferred alternative to maintaining the mass 92 stationary by friction between it and the fluid within the borehole is illustrated in Fig. 4, wherein the mass is driven to rotate at a speed faster than that of the drill stem by means of turbine blades 102 mounted on the interior surface of the rotating mass. The drill stem segment 94 in this case will incorporate a diverter 104 in the path of the high-pressure, high velocity drilling fluid 96 flowing through passageway 98, this diverter serving to direct some or all of the downhole drilling fluid through the turbine blades 102. This causes the mass 92 to rotate at a substantial speed; for example, 1000 rpm or more, to provide an inertial mass which can be used to generate torsional stress waves on the drill stem by means of the brake assembly 100.

A suitable brake assembly 100 is illustrated in cross-sectional view in Fig. 5, the assembly incorporating an hydraulically actuated brake band 110 secured at a first end 112

to the exterior of the drill stem 94, as by a suitable fastener 114. The brake band extends around the circumference of the drill stem and is secured at its opposite end 116 to a piston 118 in a hydraulic cylinder 120. The hydraulic cylinder is connected to the hydraulic line 56, described above with respect to Fig. 3, which directs fluid into cylinder 120 through fluid inlet 122. The introduction of fluid under pressure to cylinder 120 causes piston 118 to expand the brake band 110 against an interior surface 124 of the rotating mass 92. The brake band, which may be a relatively thick elastic steel ring with an appropriate brake lining, when expanded brakes the rotating mass in accordance with the operation of the electronically controlled hydraulic valve 60 under the control of the electronic package 78. Variation of the hydraulic pressure in line 56 cause the brake band to engage the rotating mass to induce corresponding torsional stress waves into the drill stem segment 94, which is rotating at a different speed than the inertial mass 92. In the case where the mass 92 is rotating at a relatively high relative speed, the brake assembly can produce relatively high frequency modulation on the drill stem using only simple and efficient hydraulics. Furthermore, the drill stem itself need not be rotating for the system to function when the mass 92 is rotating. In this embodiment, the drill stem does not need to make contact with the wall of the borehole for the system to operate. In

addition, the drill head can be lifted off the bottom and the drill stem rotational drive turned off to permit transmission of data by torsional modulation in a virtually noise-free environment.

The torsional stress modulation waves generated by the modulators described above may be detected at the surface by the drill string detection unit 42. Such a detection unit is illustrated in greater detail in Fig. 6 as including suitable strain gauge and accelerometer sensors 130 which are oriented on the drill stem 18 and balanced so as to measure torque. Such sensors are of conventional design and produce output signals on line 132 which are delivered to a telemetry unit 134 which includes conventional strain gauge sensing electronics and, in a preferred form of the invention, a radio telemetry unit 136 for transmitting the measured stress changes to the computer 36 by way of radio receiver 138. The accelerometer and the strain gauges have a large dynamic operating range so that small stress changes are readily measured.

By noting the relative phase and amplitude of the strain gauge and accelerometer signals, noise signals produced by the drive motor 22 can be suppressed relative to those which are being propagated from the downhole modulators 40 or 90. Usually, the sensitivity of measurement uphole will be limited by stresses induced by sources other than the downhole modulator. The

dominant sources of noise are the drill bit and the drill stem rotation drive. Drill bit noise is usually relatively small, in most situations, but in those cases where it is not, data can be transmitted reliably by removing the weight from the drill bit by slightly lifting the drill string. Since the rotation drive motor 22 may operate at 1000 horsepower or more, the noise it induces may be important. However, the noise spectrum of the drilling motor can be measured and an optimum frequency channel selected for the transmission of data-carrying torsional stress waves.

An alternative form of the surface detection unit 42 is illustrated in Fig. 7, wherein the detection unit utilizes an induction coil sensor 130 located on the motor control output line 30 which carries the drive current for drive motor 22. The induction coil 130 is, sensitive to changes in the current supplied to the drive motor. Torsional stresses induced downhole in the drill stem 18 vary the load on the drive motor 22 at the surface, causing the drive current to vary as the motor attempts to maintain a constant rotational speed. Such current variations correspond to the modulation of the drill stem, and accordingly the output of the sensor coil on line 132 corresponds to the data input. This output is supplied to computer 36 for use in providing information to the system operator and for utilizing

the transmitted data for controlling the operation of the system, as previously discussed.

The foregoing description has been directed primarily to methods and apparatus for transmitting data uphole, as from a location near the drill bit at the far end of a drill string, and for sensing that data at the earth's surface. However, equally important to the reliable operation of a drilling system is effective and reliable communication in the opposite direction; that is, the transmission of data from the surface to the downhole control unit. Such surface data signals may initiate the transmission of data uphole, but also provide control commands for drilling direction and dogleg severity; i.e., hole curvature.

Systems for communicating downhole are generally known, and some of these systems may utilize the rotation or nonrotation of the drill stem to switch downhole equipment on or off. However, there is a serious problem with the operation of downhole control circuitry because of the all-too-common difficulties with battery power supply units in such circuits. The batteries are often a weak point because of the adverse conditions that usually exist in downhole locations. Fig. 3 illustrates a solution to this problem, while at the same time providing an improved mechanism for reliably detecting control and data signals transmitted from the surface by modulation of the rotational speed of the drill

stem. Thus, in accordance with the invention, an electrical alternator is provided downhole and is generally indicated at 140. This alternator is responsive to the rotation of the drill stem to produce an alternating current electrical output for providing power to the downhole control unit. Furthermore, the frequency of the AC output depends on the rate of rotation of the alternator, so changes in the rotational speed of the drill stem produce modulations in the output frequency. Such modulations can be detected and then demodulated to produce transmitted data encoded in variations in drill stem rotation.

The alternator 140 includes a stator 142 incorporating a plurality of permanent magnets 143 supported on a collar 144 which is expandable against the inner wall of the borehole 20 by a plurality of bowed springs 145. These springs hold the collar stationary with respect to the rotating drill stem 18. A rotor 146 includes conventional motor windings 147 wound on laminations 148 which produce an alternating current output on line 149. This AC output is connected to a rectifier 150, and the direct current output of the rectifier is applied by way of line 157 to the drill string control unit electronics module 78. The DC current on line 150 acts as a power supply for the electronics module 78, replacing the battery pack 74 utilized in previously-described embodiments.

The AC output from the windings 142 is also supplied by way of line 149 directly to a frequency detector in the electronics module 78 by way of line 152. The frequency of the alternator output is dependent upon the rate of rotation of the drill stem 18 as noted above, and the speed of rotation of the drill stem is controllable by the motor control 28 at the surface. Control instructions and data provided at the surface by computer 36 regulate the speed of rotation of motor 22 by the motor control 28. The resulting changes in rotation of the drill stem 18 produce corresponding changes in the frequency of the output signal on line 149 which is supplied to the electronics package 78 where the frequency is demodulated to reproduce the control instructions and data from the surface.

An alternative embodiment to the rotational or torsional stress embodiments described above is illustrated in Figs. 8 and 9, to which reference is now made. In this embodiment, axial displacement modulation of the drill stem is utilized in place of rotational stress through a controllable lift mechanism which moves the drill stem longitudinally in selected increments. Thus, the embodiment of Figs. 8 and 9 includes a derrick 12 mounted on a platform 14 at the surface 16 of the earth, with the drill stem 18 being supported in a borehole 20 and driven by a top drive motor 22. The motor 22 is secured in the derrick by a conventional pulley and cable arrangement 24 for raising and

lowering the drill string, with the motor 22 being operated under the control of computer 36 by way of motor control circuit 28. Additionally, the embodiment of Fig. 8 incorporates a lift control mechanism 170 which is operated under the control of computer 36 by way of line 72 for raising or lowering the drill string 18 in increments of, for example, 3 feet, so that the drill stem can be moved the length of a conventional drill string segment in ten steps. Data to be transmitted downhole is supplied to the computer 36, which provides corresponding modulation signals on line 172 to cause the drill stem to move upwardly or downwardly in one or more steps to encode the data in axial steps of the drill stem. Because the drill stem is constructed of steel or other materials which are essentially inelastic in the axial direction, the vertical step motion of the support mechanism 170 and of the drill string at the surface is accurately and reliably transferred to corresponding steps at the drill string control unit 180, where the vertical motion is sensed and demodulated.

A suitable sensor for the axial position modulation of the drill stem 18 is illustrated in Fig. 9, wherein the control unit includes a Z-axis accelerometer 182 which produces an output on line 182 corresponding to the measured axial acceleration of the drill stem. This output, on line 184, is supplied through an integrator circuit 186 which produces output signals on line 188

for the controller module 190 which may be a computer. The control unit may include additional sensors 192, the outputs of which are supplied through decoder 194 to the control module 190, for detecting other parameters such as drill string rotation, drilling fluid flow and the like. This information may be used to control the starting or stopping of the controller 190 or for other purposes, as is known in the art. The axial position modulation solves the problem of inaccuracies that can occur in rotational modulation since in the latter case the stem can twist and thus provide inaccurate rotational data at the bottom of the drill string.

Axial stress waves can also be used to transmit data uphole through the provision of a downhole spring-loaded impact mechanism, somewhat analogous to the "jars", or shock tools, presently used for loosening stuck drill pipes. Following a predetermined control sequence of drill stem rotations and starting and stopping drill fluid flow, a powerful spring is set in the downhole assembly by applying the weight of the drill stem to the bit. The bit is then lifted slightly off the bottom to initiate a timing sequence in the downhole modulator control circuit. After a time interval which varies in accordance with the encoded data to be transmitted, the spring is released by a hydraulic cylinder. This sequence is repeated, to encode and transmit uphole data words of arbitrary length. The release of

the spring causes the drill stem to be impacted by an inertial weight associated with the spring device, and the resulting axial stress waves are detected uphole, using strain gauges and accelerometers in the detection unit 42.

The control circuit times the spring release after the drill stem is raised, and the time delay encodes the data to be transmitted in the resulting modulations of the axial stress in the drill stem. Since the timing of the impact after the drill spring is lifted can be done very precisely, data is transmitted accurately.

Axial stresses can also be generated downhole, at transducer 40, in a number of ways. Thus, for example, the transducer may be a modified joint between two adjacent segments of the drill stem 18, and is illustrated in Fig. 10 as a splined, telescoping joint 260 between upper and lower drill stem segments 262 and 264. The splined joint includes a plurality of longitudinal, spaced grooves 266 on the interior surface of the upper segment 262 which receive corresponding spaced, elongated splines 268 formed on the exterior surface of lower segment 264. The splines 268 slidably engage the grooves 266 to allow the drill segment 264 to move axially with respect to the drill segment 262 while preventing rotational motion therebetween. In this way, the drill stem can extend and contract at the transducer 40 while transmitting rotational motion from segment 262 to segment 264.

The upper and lower drill stem segments 262 and 264 are joined longitudinally by a piston and cylinder assembly 270 which includes a piston 272 movable within a cylinder 274. In the illustrated embodiment, the cylinder 274 is formed by a housing 276 mounted on or formed as a part of the lower end of drill stem segment 262, the housing being generally cylindrical and surrounding the lower end of the drill stem segment. The housing includes upper and lower radially-extending walls 277 and 277' which cooperate with the wall of the drill stem segment 262 to form the annular cylinder 274. The piston 272 is annular and is slidably mounted in the cylinder 274 to divide it into an upper chamber 278 and a lower chamber 280, the piston being sealed to the cylinder wall by O-ring 282 and to the surface of the drill stem segment 262 by O-ring 284.

Piston 272 is connected to, or formed as part of, the lower drill stem segment 264, and thus is secured to segment 264 by a connecting arm 286 in the form of a cylinder 286 and radial wall 288. The annular piston 272 is positioned within housing 276 with the connecting cylinder 286 extending through the bottom wall 277' of that housing to connect the segment 264 to upper segment 262. A pair of O-rings 290 and 292 are fixed in the lower wall 277' of housing 276 and engage the inner and outer surfaces of connecting cylinder 286 to provide a seal between the cavity 280 and the exterior of housing 276.

The upper and lower portions 278 and 280 of cylinder 274 are filled with hydraulic fluid and the two sections are interconnected through suitable valves to enable the piston 272 to move upwardly or downwardly with the cylinder. Thus, the upper section 278 is connected by way of hydraulic line 300 through a one-way check valve 302 and through hydraulic line 304 to the lower chamber 280 of the cylinder. A second valve 306, which is a solenoid-operated spool valve, connects line 304 to line 300 by way of line 308 which bypasses the check valve 302, thereby allowing fluid to flow from lower chamber 280 to upper chamber 278 of the cylinder 274 when the valve 306 is opened.

The check valve 302 allows hydraulic fluid to flow freely from upper chamber 278 to lower chamber 280 so that when there is a compressive force on the drill string; that is, when drill string segment 262 is pressed downwardly onto drill string segment 264 to compress the transducer joint 260, hydraulic fluid will flow from chamber 278 through check valve 302 to chamber 280, allowing the piston 272 to move upwardly in cylinder 274. Such a compressive force would be applied to the joint 260 when the drill string is used in its normal drilling operation, for during this time, the lift mechanism 24 on the derrick 12 lowers the drill string as it is being rotated by drive motor 22. When the drill 32 engages the bottom of the borehole, the weight of the drill string applies a compressive force on joint 260 and the

piston 272 moves upwardly in cylinder 274. The splined connection between segments 262 and 264 transmits the rotation of the drill stem 18 to the drill head 32.

During the drilling operation, or after the drilling has stopped, sensors 310 in the MWD control unit 34 produce output signals corresponding to various measured parameters, and these signals are supplied to a microprocessor 312 in the control unit. The sensors may include fluxgate magnetometers, inclinometers, gravity detectors, or like devices for measuring parameters of interest, and the sensor output signals are converted by the microprocessor to data signals which are to be transmitted to the surface. The sensors 310 and the microprocessor (or computer) 312 are conventional and, in accordance with one embodiment of the present invention, supply output signals by way of line 314 to the drill stem 18, which is of an electrically conductive material such as steel. The signals produce a corresponding electrical current in the drill stem which may be sensed at the transducer 40 by a torroidal coil 316 surrounding the drill stem segment 264. These encoded signals are supplied by coil 316 through line 318 to activate the solenoid valve 306 to open and close this valve in accordance with the encoded signals.

When data is to be transmitted uphole, the drill string 18 is lifted by the hydraulic lifters 24 at the surface so that the drill bit 32 is moved away from the bottom of the borehole. In

the preferred form of the invention, the transducer 40 is spaced about 100 meters above the drill head and its associated MWD control unit 34. This causes the weight of the lower end of the drill stem below the modulator, which may be 5000 lbs., or more, to tend to extend the joint 260 and thus tend to pull the piston 272 downwardly, applying a high pressure to the hydraulic fluid in chamber 280. As long as valve 306 remains closed, the hydraulic fluid will be retained in chamber 280 and the joint will be held in its collapsed or upward position, with the piston 272 at the top of cylinder 274. The control signals from microprocessor 312 may then be used to activate and deactivate the solenoid valve in short, timed bursts, allowing pressurized hydraulic fluid to flow out of chamber 280, through valve 306 and line 308 to upper chamber 278. This releases segment 264 in incremental steps, and the portion of the drill string 18 below the modulator drops freely until the valve is closed. Each burst of released fluid thus momentarily releases the tension or axial stress applied to the upper part 262 of the drill string 18 by the weight of the drill stem below the transducer, and thus reduces the apparent drill string weight that is detected by sensors 42 at the surface. The change in axial stress caused by opening of valve 306 is transmitted along the length of the drill string above the transducer for detection at the surface, and such a release is referred to herein as an axial stress wave or

a shock wave. Repeated openings and closings of the valve 306 in accordance with encoded signals produced by microprocessor 312 produce corresponding stress pulses, or shock waves, which travel along the length of the drill stem to the surface for detection at sensor 42 and for decoding in computer 36.

If desired, the drill string can be rotated during the transmission of shock waves uphole, so that the rotation eliminates the effects of stick slip friction between the upper part of the drill string and the borehole wall, thereby increasing the efficiency of the modulated axial stress transmission.

Because of changes in ambient pressure as the drill string is moved downwardly in a borehole, the hydraulic cylinder 274 may be connected to an accumulator 330 which may be connected to the upper chamber 278 by way of a small passageway 332. The accumulator 330 preferably is an elastomer that allows expansion to accommodate small ambient pressure changes.

To have efficient modulation of axial stress in accordance with the foregoing embodiment, the spline section of the drill stem should be a significant distance above the drill bit so that a large drill string weight will be carried by the hydraulic cylinder fluid. Although the data transmission from the control unit 34 is by way of the drill stem in the illustration, the control unit 34 can be connected to solenoid valve 306 by a

direct wire, if desired. Power for the control unit can be by way of a battery source, or can be supplied by an alternator in the manner described above.

A modified form of the downhole transducer is illustrated in Fig. 11 at 40'. In this case, however, the piston and cylinder arrangement of the embodiment of Fig.10 is reversed so that hydraulic fluid is transferred between upper and lower chambers of the cylinder to charge the transducer by lifting the drill string. Then, when drilling is started the weight of the string applies high pressure to the fluid in the lower chamber of the cylinder so that release of that high pressure fluid by a solenoid-controlled valve produces short bursts of reduced pressure to incrementally lower the portion of the drill string and generates axial stress waves which can be detected at the surface. One advantage of this arrangement is that the transmission of data can be carried out during drilling.

As was the case with the embodiment of Fig. 10, the modified transducer 40' incorporates a splined joint 130 between an upper drill stem segment 332 and a lower segment 334. The upper segment 332 is connected as a part of the drill stem 18 and leads to the surface, while segment 334 is connected through the control unit 34 (Fig.1) to the drill head 32. In the embodiment of Fig. 10, the transducer 40 is separated from control unit 34 and drill head 32 by a distance of about 100 meters in order to

provide sufficient weight to produce axial stress waves upon operation of the solenoid valve. In the present embodiment, however, the transducer 40' can be close to the control unit 34 and drill head 32, since it is the weight of the drill string above the transducer that produces the desired stress signals upon the release of pressurized fluid by the solenoid valve.

In the structure of Fig. 11, segment 332 carries on its interior surface 336 a plurality of longitudinally extending grooves 338. These grooves receive corresponding splines 340 carried on the exterior surface of lower drill stem segment 334, thereby forming the splined joint 330. This joint permits relative longitudinal movement between the lower drill stem segment 334 the upper segment 332.

Surrounding the spline joint 330 is a cylindrical housing 342 which is mounted on, or is integral with, the stem segment 334 at a lower wall portion 344 and extends upwardly to a top wall portion 346 which engages the outer surface of stem portion 332. The wall 346 carries a suitable seal 348 such as an O-ring to provide a fluid tight transducer cylinder 350, defined by cylindrical housing 342.

Located within cylinder 350 and dividing the cylinder into upper and lower chambers 352 and 354 is an annular piston 356 which is secured to or is integral with the bottom end of the drill stem segment 332. As illustrated, the piston 356

incorporates an O-ring 358 which seals it against the wall of cylinder 350 to maintain a fluid-tight seal between chambers 352 and 354. The two chambers are filled with hydraulic fluid such as oil, with the upper chamber being connected to the lower chamber by way of hydraulic lines 360 and 362, check valve 364, and hydraulic lines 366, 368 and 370. The check valve 364 permits the fluid from chamber 352 to flow downwardly into chamber 354, in the direction of arrow 372, so that when the drill stem 18 is lifted by the lift equipment 24 (Fig. 1) the piston 356 will tend to move upwardly in cylinder 350 and force hydraulic fluid from chamber 352 down through check valve 364 into chamber 354. This charges the transducer to make it ready for the transmission of data signals to the surface.

Bypassing the check valve 364 is a solenoid-operated control valve 374 which is connected between hydraulic lines 360 and 368 by way of hydraulic lines 376 and 378. The valve 374 is normally closed to prevent the flow of fluid between lines 376 and 378, but upon energization of the solenoid, the valve shifts into an open position to allow fluid flow.

In operation, after the chamber 354 has been charged with hydraulic fluid by lifting the drill stem 18, the stem is lowered by lift equipment 24 and, if desired, can be driven by motor 22 (Fig.1) for continued drilling of the borehole. The weight of the drill stem which is applied to the drill head 32 is applied

through the hydraulic fluid in chamber 354 by way of piston 356, generating as much as 20,000 lbs./sq.in. of fluid pressure in chamber 354, which then serves as a pressure chamber. The splined joint 330 transmits the rotation of drill stem 18 through the transducer and to the drill head 32.

Downhole sensors 310 in the control unit 34 produce output signals corresponding to sensed parameters, and these signals are directed to a microprocessor, or other suitable computer 312, as described above, which produces encoded data signals on line 314. In the embodiment of Fig.3, line 314 is shown as being directly connected to solenoid valve 374 so that the output signals from computer 312 control the operation of the valve. Thus, the valve is energized by data signals to shift to an open position for a short period of time and then to shift back to the closed position, thereby releasing fluid under pressure from pressure chamber 354 and allowing it to flow through lines 370, 368, 378, 376, and 360 into the upper chamber 352, which serves as a release chamber. This allows the piston 356 to shift downwardly a small amount, the distance depending upon the duration of the data pulse. The shift of the piston produces an axial stress wave in the drill stem 18 which travels along the length of the drill stem and can be detected at the surface by sensor 42, in the manner described above, thereby accurately transmitting the

data from computer 312 at the downhole location to computer 36 at the surface.

As illustrated, hydraulic system of Fig.11 may incorporate an accumulator 380 connected to hydraulic line 360 to accommodate variations in the temperature of the fluid, for example, and may include a pressure sensor 382 connected to hydraulic line 368 for measuring the pressure in chamber 354. The electrical output from sensor 382 may be connected by way of line 384 to computer 312, so that the pressure in chamber 354 may be one of the parameters included with the data signals on line 314.

Although the preferred method for charging the pressurized chamber 354 is by lifting the drill stem 18, charging of the chamber can also be accomplished by supplying hydraulic fluid under pressure to line 370, as from an hydraulic pump located downhole. A suitable pump for this purpose is illustrated at 400 in Fig. 12, the pump including an hydraulic cylinder 402 mounted on and surrounding a section of drill pipe such as the drill stem segment 334. The cylinder 402 receives a free piston 404 which is annular in shape, which surrounds the drill stem segment 334, and which is moved along the length of cylinder 402 by varying the fluid pressure in the cylinder. The piston includes an inner annular surface 405 carrying an O-ring 406 for sealing against the exterior of drill stem segment 134. It also has an outer annular surface 407 incorporating an O-ring 408 for sealing the

piston against the wall of cylinder 402 so the piston divides the cylinder into an upper recharging chamber 410 and a lower pumping chamber 412. The upper chamber contains hydraulic fluid to be supplied through outlet line 414, and through a check valve 416 to a gear-type pressure multiplier which provides a pressure increase in the hydraulic fluid. This increased pressure fluid is supplied from the pressure multiplier through line 370 to the lower pressure chamber 354 in transducer 40' to recharge it. Pressurized fluid supplied from pump 400 thus may be used to charge chamber 354 to a desired pressure level. The multiplier 418 is connected by way of a second outlet line 423 and a second check valve 424 to return excess fluid to chamber 410.

Pressure is generated in recharging chamber 410 by means of the conventional drilling fluid, or drilling mud, used in rotating drilling systems. Thus, drilling fluid flows downwardly into the bottom of the borehole through the center of the drill stem 18 and is under about 500 psi at the bottom of the borehole. A small part of that drilling fluid is supplied from the interior of drill stem segment 334 through a feed line 430, through a solenoid valve 432, and through a supply line 434 to the pumping chamber 412 of cylinder 402. When the solenoid 432 is open, as illustrated, drilling fluid is supplied to chamber 412 to press piston 404 upwardly to thereby pressurize the hydraulic fluid in chamber 410. This causes hydraulic fluid to flow to pressure

chamber 354 in the transducer of Fig. 11 to charge the transducer.

The sensor unit 310 may incorporate a sensor for detecting the location of piston 404 in cylinder 402 to enable the computer 312 to regulate the operation of solenoid control valve 432. If the piston 404 shifts upwardly too far, valve 432 may be shifted to the left (as viewed in Fig. 12) to connect the fluid line 434 through the solenoid valve to an outlet line 436. This allows the drilling fluid in chamber 412 to bleed out of the system and to return to the borehole annulus surrounding drill stem 18. The piston 404 then falls to expand chamber 410, with fluid from accumulator 422 filling the chamber. When sufficient hydraulic fluid has been supplied to chamber 410, valve 432 is shifted to the right to open line 434 to inlet line 430 to thereby allow the drilling fluid to pressurize chamber 412. The pump 400 thus is operated by means of the drilling fluid circulating into the borehole through the drill stem to keep the axial stress transducer 40' charged and activated.

Axial pressure waves generated by released pressure in downhole transducers 40 or 40' may be detected at the surface by sensor 42, which may incorporate suitable strain gauges, as described above. However, axial stresses generated downhole can also be measured at the surface as pressure variations in a hydraulic transducer such as that illustrated at 42' in Fig. 13.

This transducer is similar to that described above with respect to Fig.11, but utilizes a pressure sensor coupled to the upper chamber for detecting changes in hydraulic pressure due to axial stress waves received along drill string 18. The output of the pressure sensor may then be transmitted to the uphole computer 36 by way of line 44 or by any other conventional communications link.

The uphole transducer 42' includes a cylinder 440 surrounding a telescoping splined joint 442 formed between adjacent upper and lower drill stem segments 444 and 446. Segment 444 includes a plurality of longitudinal, spaced grooves 448 located at the lower end of its inner surface, while the upper end of segment 446 includes a corresponding plurality of longitudinal splines 450. As previously described, the splined joint allows relative longitudinal motion between segments 444 and 446, while transmitting rotary motion from one to the other. Cylinder 440 receives an annular piston 452 which may be integral with the bottom of drill stem segment 444 and which divides the cylinder 440 into an upper pressure chamber 454 and a lower chamber release chamber 456. Suitable O-rings 457 and 458 seal the piston against the wall of cylinder 440 and seal the cylinder 440 against the outer surface of segment 444. The segment 444 is supported by the lift mechanism 44 and is connected to the drill stem 18 extending into the borehole by the transducer 42'. Thus,

the hydraulic fluid in chamber 454 between piston 452 and cylinder 440 supports the weight of the drill and as a result is under high pressure.

In operation, stress pulses from the transducers 40 or 40' received at the surface tend to reduce or increase the pressure of the hydraulic fluid in chambers 454 and 456 as segment 446 tends to shift axially with respect to segment 444. Such changes in pressure in chamber 454 and 456 are detected by a pressure sensor 460 connected by way of line 462 to the upper chamber 454, for example, with the output of sensor 460 being transmitted by way of a communication link 44 to the computer 36.

The transducer 42' can also be used to transmit data downhole by generating axial stress waves. In this mode of operation, the hydraulic fluid pressure in cylinder 440 is released in short, timed bursts under the control of a solenoid valve, operated by encoded signals from computer 36 generally in the manner described hereinabove with respect to Figs. 2 and 3. The resulting stress signals, or shock waves, are transmitted through the drill stem 18 to the downhole transducer 40 or 40'. These stress signals produce pressure changes in the hydraulic fluid in the downhole transducer, such as the transducer 40' discussed with respect to Fig. 11, and such pressure changes are detectable by the pressure sensor 382 (Fig.11). The resulting output signals from sensor 382 are supplied to computer 312 at

the downhole location for demodulation to allow the computer to exercise control over the downhole operations.

Stress signals are generated in the drill string at the uphole transducer 41' by releasing the pressure chamber 454 by way of hydraulic lines 462 and 466, a solenoid-controlled spool valve 468, and hydraulic lines 470 and 464. Encoded data or control signals to be transmitted downhole are provided by computer 36 on line 472, and these signals operate solenoid valve 468. The normally closed valve is activated by the encoded signals to allow fluid to flow from upper chamber 454 to lower chamber 456 in timed bursts to produce incremental motion or variations in longitudinal tension or compression in drill stem segment 446 to produce axial stress signals.

Chamber 454 can be charged with hydraulic fluid and the location of piston 452 in the cylinder 440 can be adjusted by lowering the drill stem 18 to the bottom of the borehole and then further lowering the upper drill segment 444 while opening solenoid valve 468, thereby allowing a reverse flow of fluid from chamber 456 to chamber 454. Fluid may also be transferred to chamber 454 from an accumulator 474 connected to line 470. Alternatively, the upper chamber can be charged by means of an hydraulic pump 476 connected to the lower chamber 456 through accumulator 474 and hydraulic line 464, the pump delivering pressurized fluid through line 478 and a second solenoid-

controlled spool valve 480, the output of which is connected by way of lines 482 and 462 to the upper chamber 454. Upon operation of pump 476, under the control of computer 36, hydraulic fluid under pressure may be supplied to the upper chamber to raise the drill segment 446 with respect to drill segment 444 and to thereby charge the upper chamber 454. Sufficient power to operate such a pump is normally available at the surface.

By providing transducers such as 40 or 40' at the bottom of the drill string and a transducer such as that shown at 42' at the top of the drill string, two-way communication within the borehole by means of axial stress waves is accomplished. Such a communication system provides rapid feedback control of the weight on the drill bit at the bottom of the drill string by controlling the position of piston 452 in cylinder 440. This permits rapid control of stick-slip problems in the drill bit and permits control and modulation of the torque applied to the drill by raising and lowering the drill stem.

The rapid communication between the surface and the drill controls at the bottom of the borehole provided by the present invention also permits conservation of the energy required for such communication, for if strong signals are received at the surface, computer 36 can transmit instructions to the downhole

computer to change the frequency and strength of the pulses to reduce the energy required.

The downhole solenoid valves are battery-operated, in the preferred form of the invention, and as discussed above, the downhole units send data by releasing small volumes of hydraulic fluid in timed increments using these solenoid-operated valves to impulsively lower the drill string and generate axial stress waves which propagate to the surface. At the surface the stress waves are demodulated by strain gauges or by an axial stress transducer located at the top of the drill string. This upper transducer is of heavier construction than the downhole units because of the large weights which it must handle. In a preferred form, it does not require a check valve for recharging the hydraulic chambers, but instead is kept activated by a secondary source of pressurized hydraulic fluid under the control of a second solenoid valve.

Incoming axial stress wave pulses to the uphole transducer are sensed by pressure changes, with the pressure sensor sending corresponding signals to the computer for demodulation. By using two axial stress demodulators, one at the top of the drill and one at the bottom, a two-way communication system is provided. The hydraulic energy for the downhole transducer is provided by the downward pressure of the drill string or, in the alternative, by a secondary source of pressurized hydraulic fluid such as a

pump driven by the drilling fluid which flows to the drill bit through the center of the drill string. This allows the downhole axial stress transducer to continually send data pulses to the surface while the drill is operating, without the need to re-energize the unit by lifting the drill string at the surface.

An important feature of the invention is that the intrinsic fast response and huge power gain which can be built into electrically-controlled hydraulic valves, coupled with the intrinsic high frequency wave propagation characteristics of the drill stem, enables drilling parameters to be controlled by a fast acting communication system.

An important application of this system is the possibility of significantly reducing the effects of erratic stick-slip behavior in aggressive PDC drilling bits. Thus, the transmission of data from the downhole transducer has the effect of modulating the drilling weight on the bit. As the weight on the bit is changed, its bite into the formations being drilled also changes, producing an immediate change in drilling torque which can be sensed by a strain gauge on the drill stem near the drilling bit. Such a strain gauge is diagrammatically illustrated at 490 in Fig. 1, with the output of the strain gauge being connected to the microprocessor, or computer, 312 in the control unit 34. By noting the ratio between the applied drilling weight fluctuations and the resulting torque fluctuations, a continuous measurement

of the dynamic aggressiveness of drilling can be measured. This parameter can be transmitted uphole to the surface transducer, where it is received within a second, and can be used to change immediately the weight on the bit by activating the solenoid-controlled spool valve 480 which controls the position of the piston 452 in the uphole axial stress transducer 42' from which the drill stem hangs.

The velocity of propagation of compressive waves in steel is about 500 m./sec., the acoustic impedance of steel (density x velocity of propagation) is 4 x 10^7, and the cross sectional area of a drill string is about 0.006 m^2. The wave power associated with 1000 lbs./in^2 ($7x10^6$ newtons/m^2) stress waves on such a drill string is approximately 10,000 watts; that is, 13 horsepower. The energy available from lowering a drill stem 1 meter with 20,000 lbs. of force (which is a characteristic weight on a drilling bit) is 88,000 joules. Measurement of drill bit vibrations at the earth's surface show that compressional waves with frequencies as high as 100 Hz are readily transmitted on the drill stem. The simplest hydraulic spool valve energized by 20 watts of electric power can control a flow of 30 gallons per minute at 3000 psi; that is, 44,000 watts of hydraulic power. The response time of such valves is 0.003 seconds, so that 10 Hz waves are readily generated. The peak drill string movement

associated with a 10 Hz, 1000 psi wave is about 3 mm, thus indicating the practicality of the present communication system.

Thus, there has been disclosed a unique system for data communication between the surface and downhole locations in a drill string with a high degree of accuracy and reliability. In addition, in one embodiment of the invention, the sensor mechanism also serves as a power source for supplying operating power to downhole equipment, thus avoiding the need for batteries and extending the life of the equipment. Although the invention has been described in terms of preferred embodiments, it will be apparent that numerous modifications and variations can be made without departing from the true spirit and scope of the invention as set forth in the accompanying claims.

WHAT IS CLAIMED IS:

1. Apparatus for providing a data link borehole, comprising:

a rotatable drill stem;

a data source;

a modulator connected to said data source and coupled to said drill stem at a first location for varying stress in said drill stem in accordance with data to be transmitted;

a sensor coupled to said drill stem at a second location for detecting variations in stress applied to said drill stem and for producing an output signal corresponding to said variations; and

a demodulator connected to said sensor to produce an output corresponding to said data.

2. The apparatus of Claim 1, wherein said modulator is coupled to said drill stem through a rotary drive motor to vary said stress by varying the speed of rotation of said drill stem.

3. The apparatus of Claim 2, wherein said sensor is an electrical alternator coupled to said drive stem, said alternator producing an output signal corresponding to the rotation of said drill stem.

4. The apparatus of Claim 3, wherein said alternator output signal has an amplitude corresponding to the rate of rotation of said drill stem and modulated in accordance with said variation in said speed of rotation.

5. The apparatus of Claim 4, further including:

drill control circuitry at said second location;

a demodulator in said control circuit for receiving and demodulating said alternator output to provide said data to said control circuit; and

a power supply circuit for receiving said alternator output and for supplying operating power to said control circuitry.

6. The apparatus of Claim 5, further including:

a second data source in said control circuitry at said second location;

a second modulator at said second location responsive to said second data source and coupled to said drill stem to vary the stress in said drill stem in accordance with said second data;

a second sensor coupled to said drill stem at said first location to detect variations in the stress in said drill stem; and

a second demodulator coupled to said second sensor to reproduce said second data at said first location.

7. The apparatus of Claim 6, wherein said first location is at the earth's surface and said second location is downhole in a borehole being drilled.

8. Apparatus for providing a communication link in a borehole, comprising:

a drill stem extending from the earth's surface into a borehole;

a source of encoded signals corresponding to data to be transmitted between first and second locations along said drill stem;

an hydraulic transducer connected to said data source and

coupled to said drill stem at one of said first and second locations for varying axial stress in said drill stem in accordance with data to be transmitted; and

a sensor coupled to said drill stem at the other of said

first and second locations for detecting variations in axial stress applied to said drill stem and for producing a corresponding output signal.

9. The apparatus of claim 8, wherein said transducer hydraulically couples first and second segments of said drill stem to provide controlled relative axial motion between said segments.

10. The apparatus of claim 9, wherein said sensor is a second hydraulic transducer producing an output signal corresponding to axial stress applied to said drill stem.

11. The apparatus of claim 9, wherein said transducer is coupled to said first and second segments of said drill stem so as to transmit rotational motion of one segment to the other segment.

12. The apparatus of claim 11, wherein said first and second segments are adjacent to each other, and wherein said adjacent segments are coupled by a splined joint which permits relative axial motion.

13. The apparatus of claim 9, wherein said transducer includes an hydraulic cylinder containing hydraulic fluid and incorporating a movable piston which divides the cylinder into a

pressure chamber and a release chamber, said piston being connected to one of said drill stem segments and said cylinder being connected to the other to one of said drill stem segments and said cylinder being connected to the other of said drill stem segments.

14. The apparatus of claim 13, further including means interconnecting said pressure and release chambers and controllable to regulate the position of said piston in said cylinder.

15. The apparatus of claim 14, wherein said interconnecting means includes an hydraulic line including a controllable valve.

16. The apparatus of claim 14, wherein said interconnecting means includes means responsive to said encoded signals to produce corresponding movement of said piston.

17. The apparatus of claim 9, wherein said hydraulic transducer includes means responsive to said encoded signals to produce corresponding variations in said axial stress.

18. The apparatus of claim 9, wherein said hydraulic

transducer includes an hydraulic pressure chamber containing hydraulic fluid under pressure, and means responsive to said encoded signals to release said fluid incrementally to produce corresponding axial stress signals in said drill stem.

19. The apparatus of claim 18, further including means for charging said hydraulic pressure chamber.

20. The apparatus of claim 9, wherein said transducer is located in said borehole at said first location and is responsive to said encoded signals to produce said variations in axial stress in said drill stem.

21. The apparatus of claim 20, wherein said sensor is a strain gauge mounted on said drill stem at said second location.

22. The apparatus of claim 20, wherein said sensor is a second hydraulic transducer coupled to third and fourth segments of said drill stem at said second location.

23. The apparatus of claim 22, wherein said first-named transducer is located downhole is located at the earth's surface, each of said first-named and second transducer being operable to

generate and to sense axial stress waves in said drill string for two-way communication.

24. The apparatus of claim 22, wherein said transducer includes an hydraulic fluid pressure chamber and a controllable valve for incrementally releasing hydraulic fluid from said chamber to varying said axial stress in said drill stem.

25. The apparatus of claim 24, further including a recharging source for recharging said fluid pressure chamber.

26. The apparatus of claim 25, wherein said recharging source includes a check valve connected between a fluid supply and said pressure chamber.

27. The apparatus of claim 25, wherein said recharging source includes an hydraulic pump connected between a fluid supply and said pressure chamber.

28. The apparatus of claim 27, wherein said hydraulic pump includes a cylinder and a floating piston dividing the cylinder into a pumping chamber and a recharging chamber, the pumping

chamber being connected to a source of drilling fluid in said borehole and said recharging chamber being connected to said pressure chamber in said transducer.

29. The apparatus of claim 25, wherein said sensor comprises

a second transducer having an hydraulic fluid pressure chamber.

30. The apparatus of claim 29, wherein said transducer further includes a second controllable valve for incrementally releasing hydraulic fluid from said chamber for varying said axial stress in said drill stem to provide two-way communication between said first and second locations.

31. A method for transmitting data along a drill string, comprising:

applying a stress to said-drill string at a first location along the string;

sensing, at a second location along the drill string, said stress waves.

32. The method of claim 31, wherein applying a stress

includes applying a rotational force to said drill string to produce a torsional stress.

33. The method of claim 31, wherein applying a stress includes applying an axial force to said drill string to produce an axial force.

34. The method of claim 31, wherein modulating said stress includes varying the applied stress in accordance with selected signals.

35. The method of claim 34, wherein sensing said stress waves

includes measuring variations in said stress to permit reproduction of said selected signals.

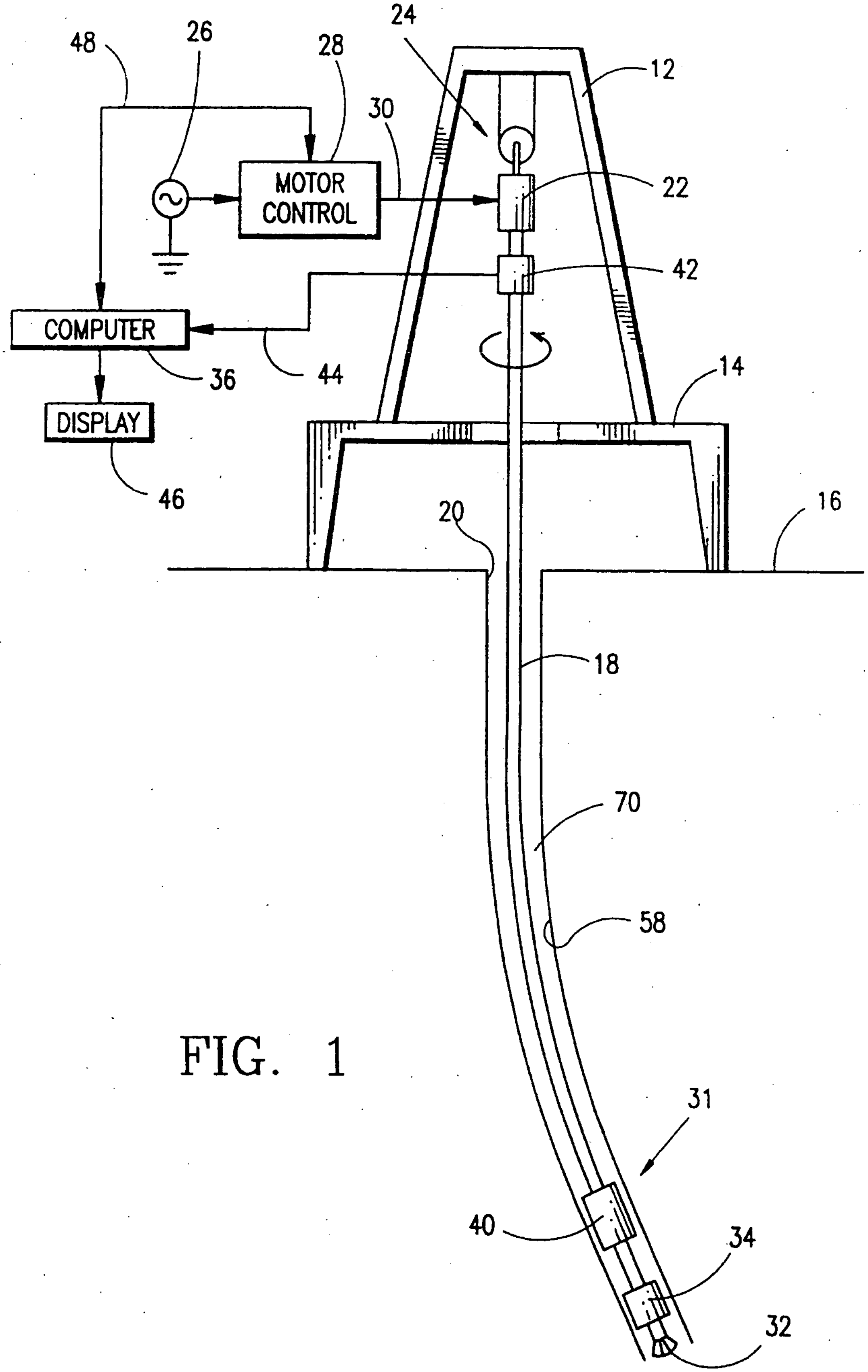
48
26
28
24
12
30
MOTOR CONTROL
22
42
COMPUTER
36
44
DISPLAY
46
14
20
16
18
70
58
31
40
34
32

FIG. 1

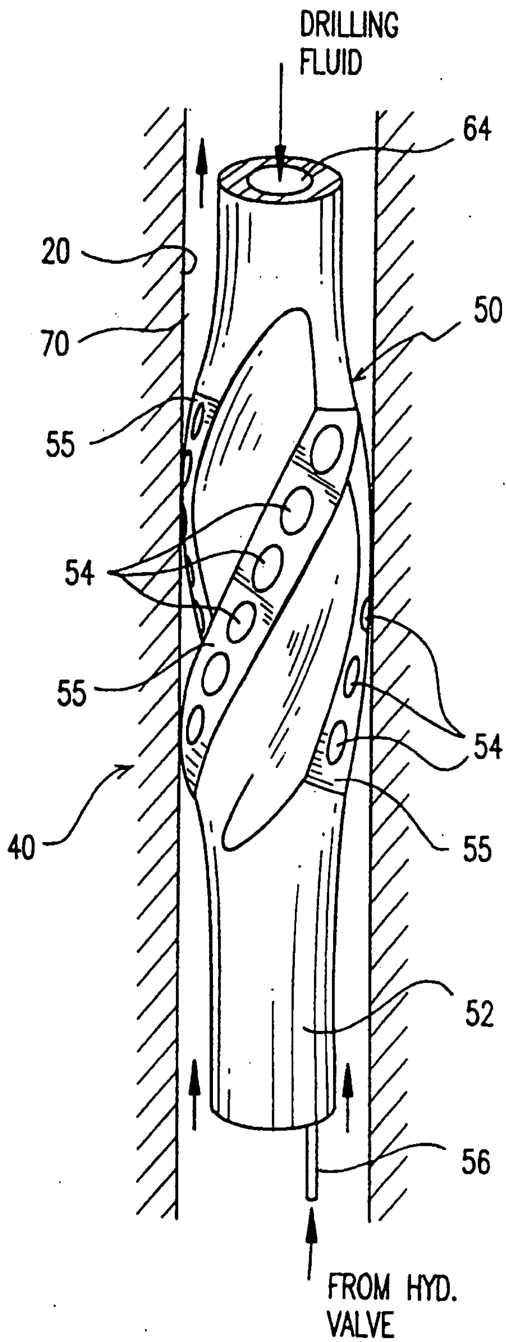

FIG. 2

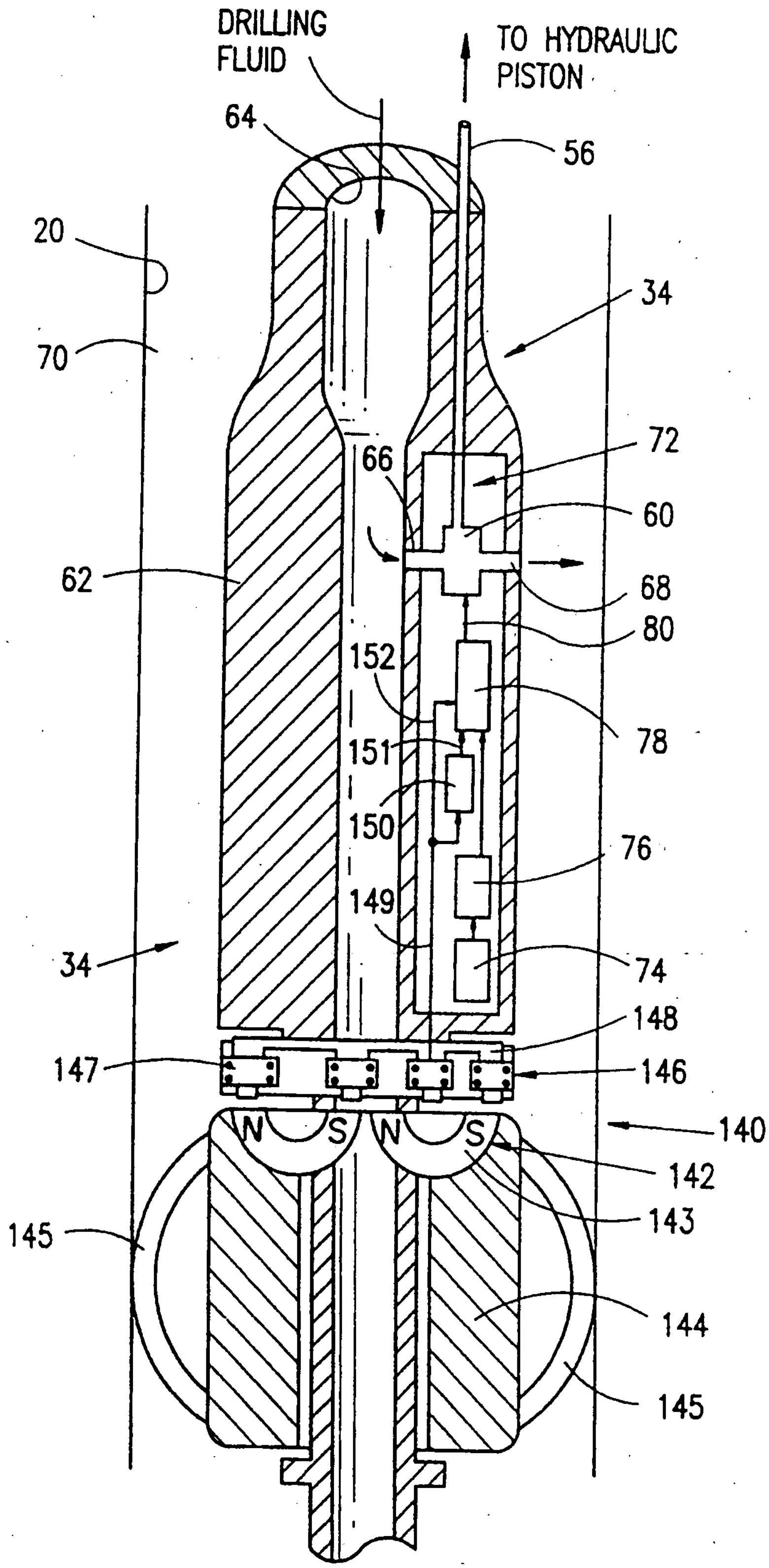
DRILLING FLUID
TO HYDRAULIC PISTON
64
56
20
34
70
72
66
60
62
68
80
152
78
151
150
76
149
34
74
148
147
146
140
N
S
N
S
142
143
145
144
145

FIG. 3

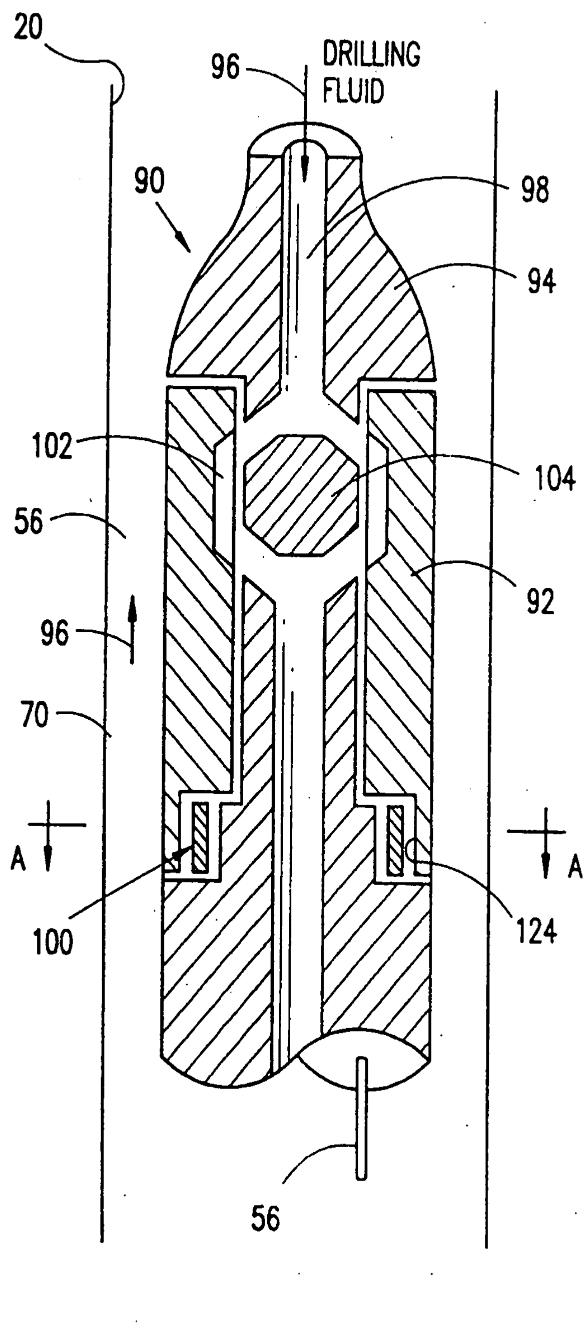

FIG. 4

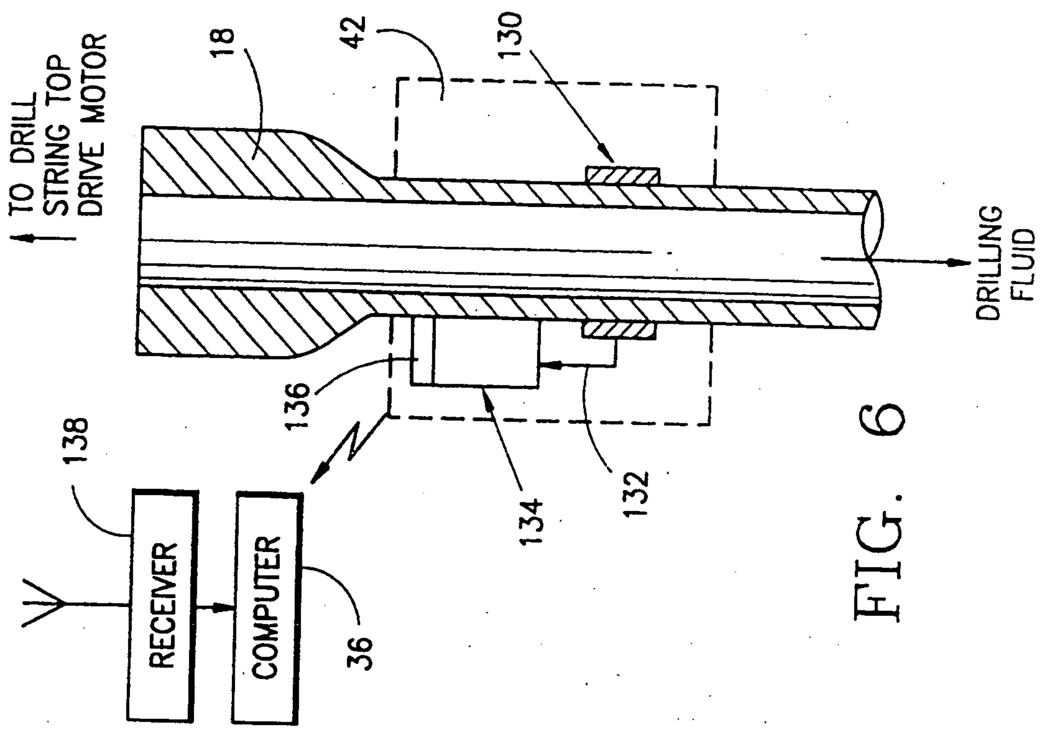
TO DRILL STRING TOP DRIVE MOTOR
18
42
130
DRILLING FLUID
138
136
134
132
RECEIVER
COMPUTER
36

FIG. 6

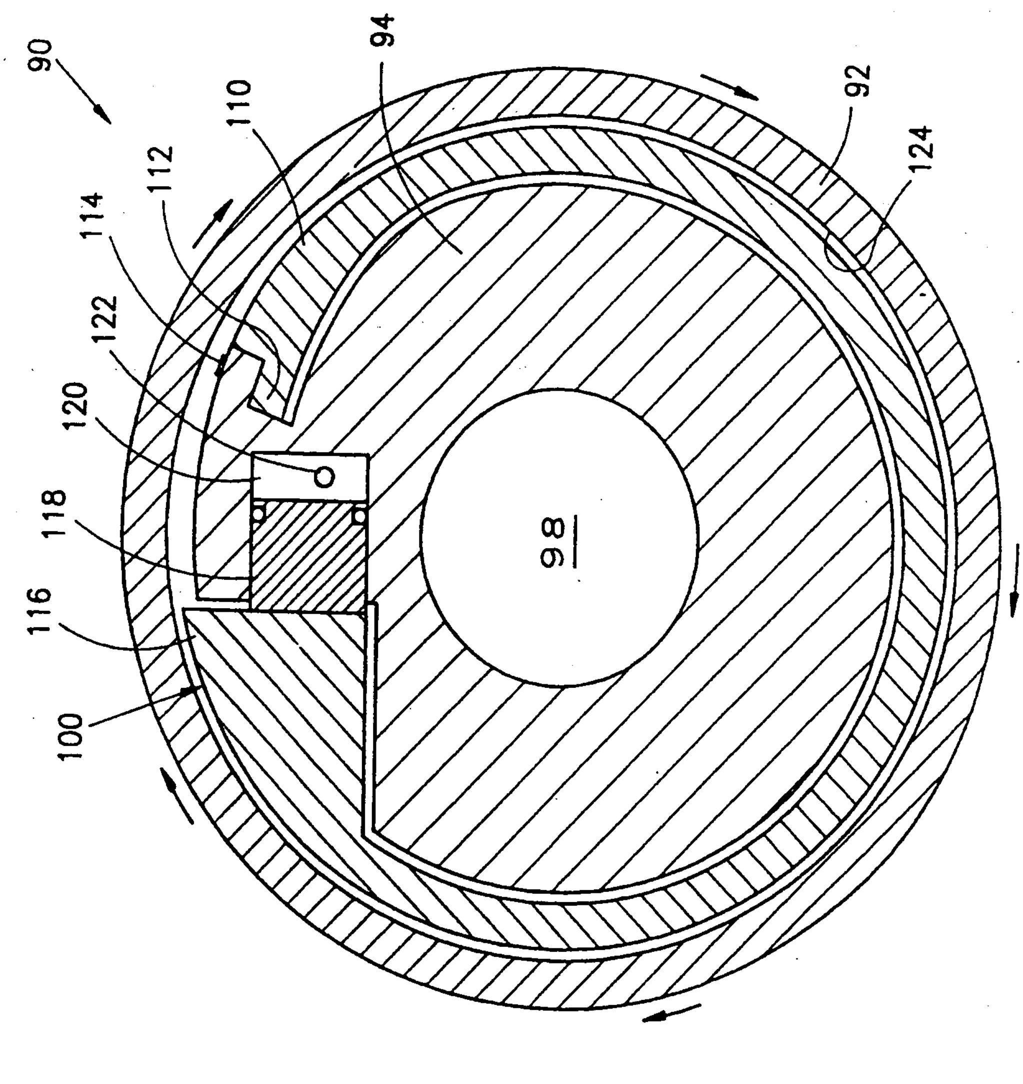
90
94
92
124
110
112
114
122
120
118
116
100
98

FIG. 5

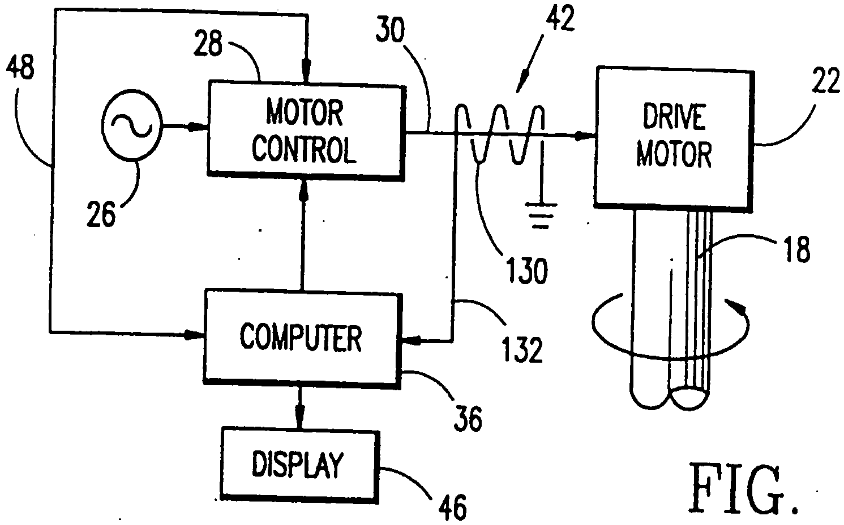
48
28
30
42
MOTOR CONTROL
DRIVE MOTOR
22
26
130
18
COMPUTER
132
36
DISPLAY
46

FIG. 7

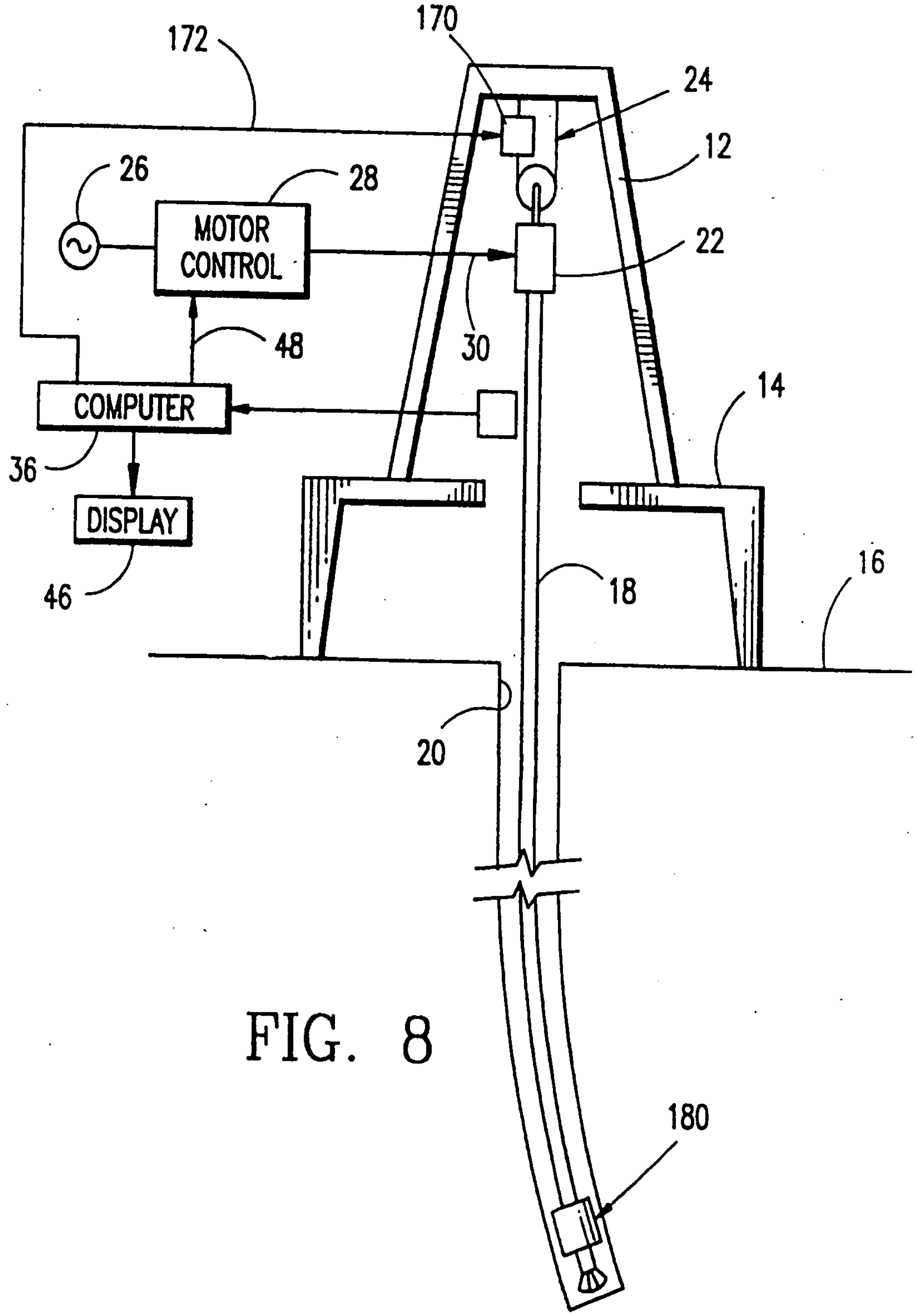
172
170
24
12
26
28
MOTOR CONTROL
22
48
30
COMPUTER
14
36
DISPLAY
16
18
46
20
180

FIG. 8

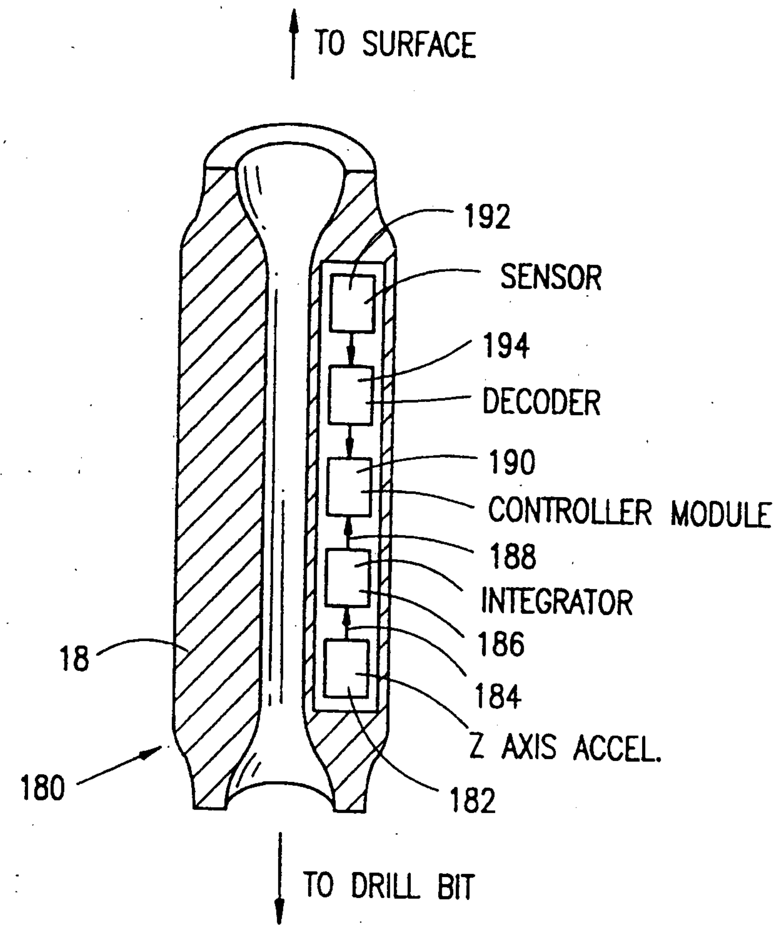
TO SURFACE
192
SENSOR
194
DECODER
190
CONTROLLER MODULE
188
INTEGRATOR
186
184
Z AXIS ACCEL.
182
18
180
TO DRILL BIT

FIG. 9

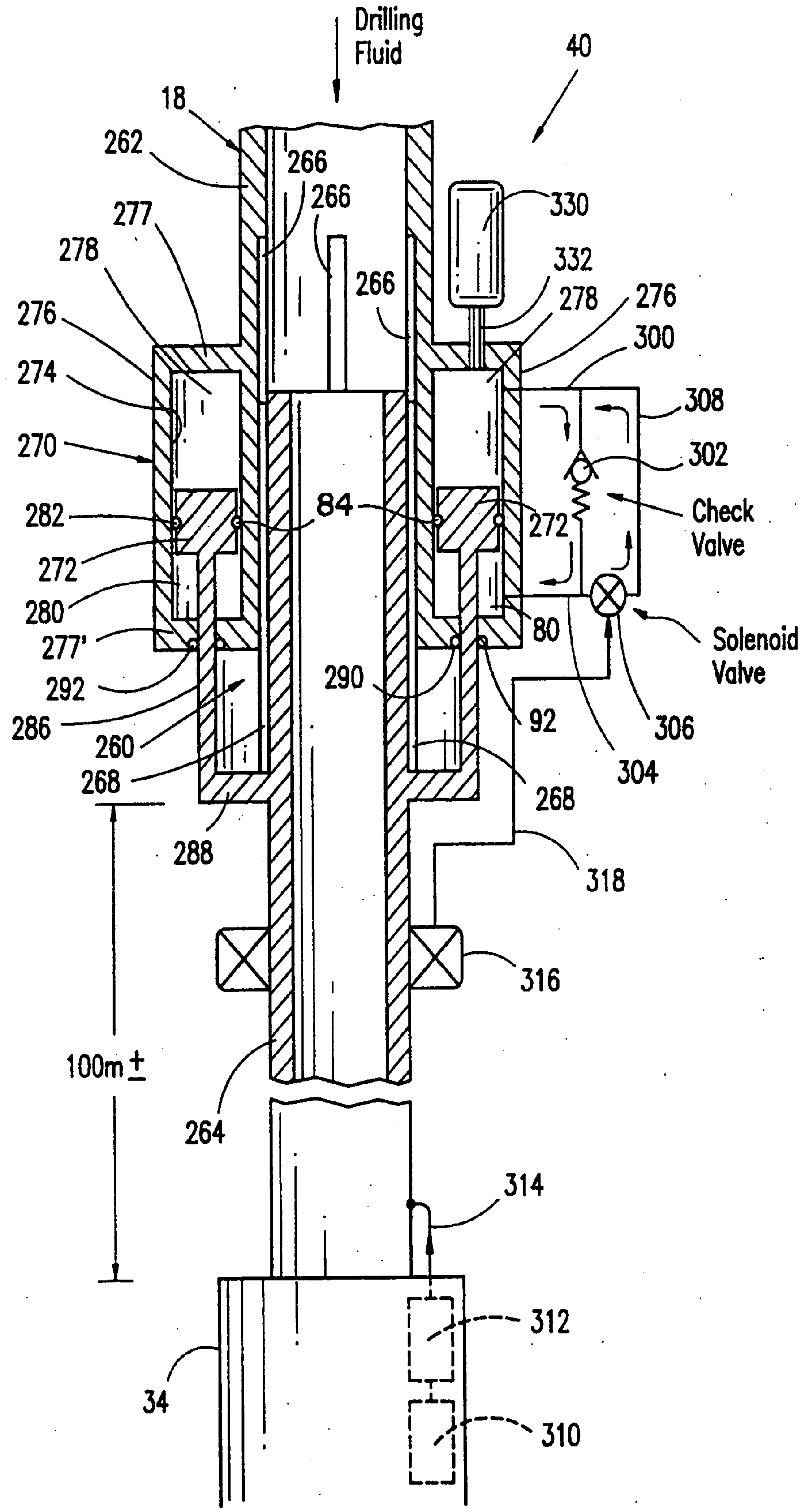
Drilling Fluid
40
18
262
266
266
266
330
332
277
278
278
276
276
300
274
308
270
302
282
84
272
Check Valve
272
280
80
277'
Solenoid Valve
292
290
92
306
286
260
304
268
268
288
318
316
100m ±
264
314
312
34
310

FIG. 10

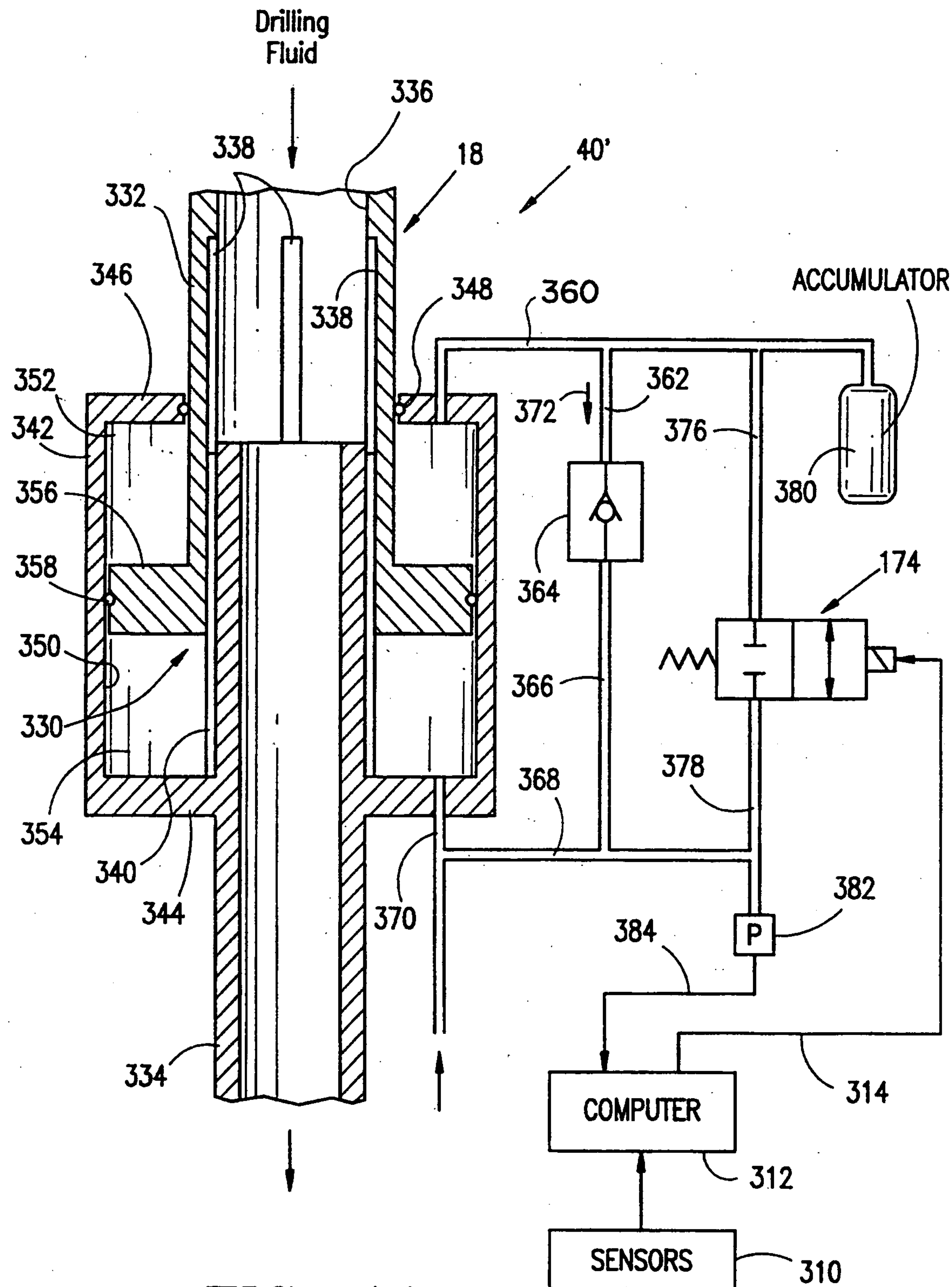
Drilling
Fluid
336
338
18
40'
332
346
338
348
360
ACCUMULATOR
352
342
372
362
376
380
356
364
174
358
350
366
330
368
378
354
340
344
370
382
384
P
334
COMPUTER
314
312
SENSORS
310

FIG. 11

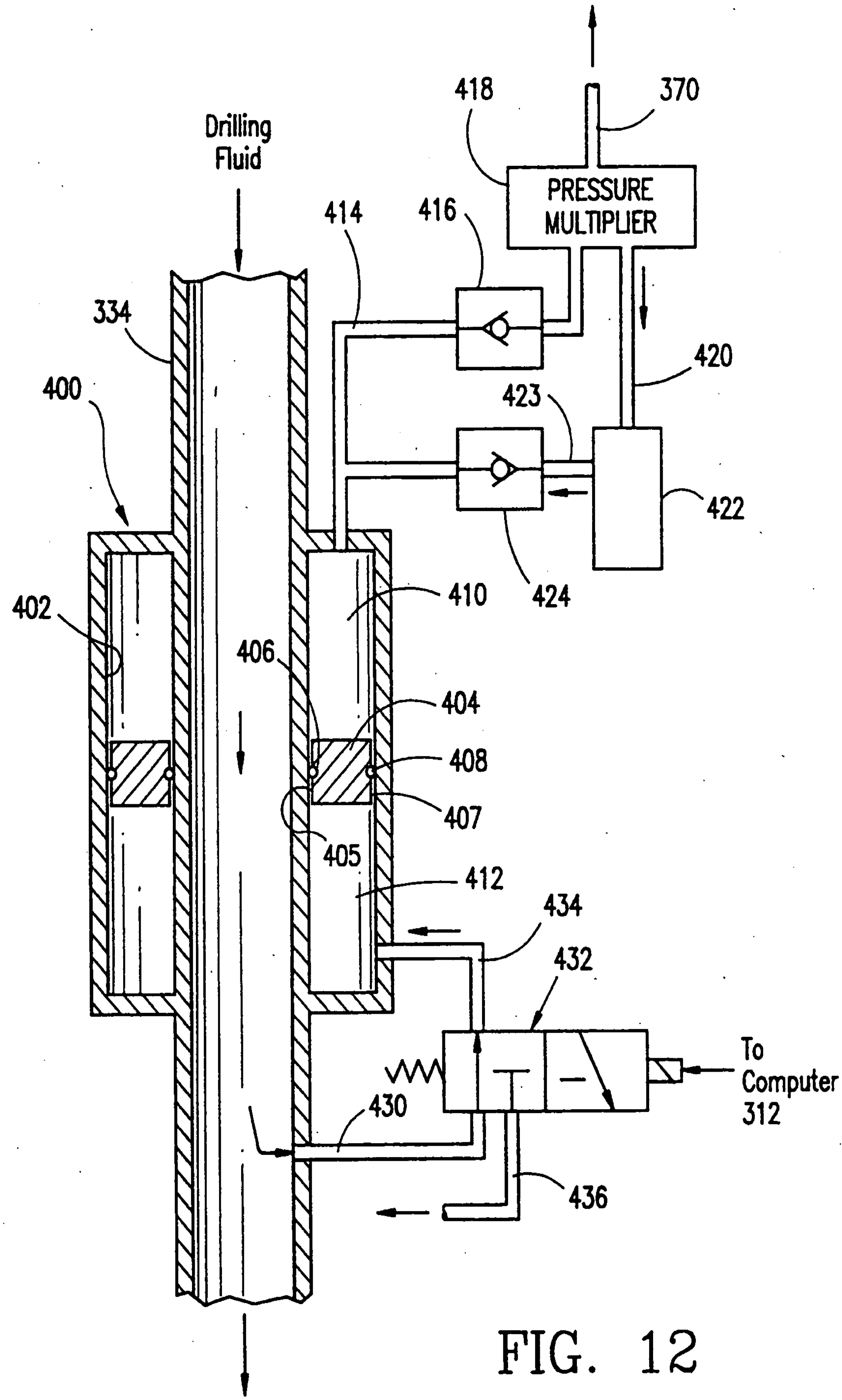
Drilling Fluid
PRESSURE MULTIPLIER
418
370
414
416
334
400
420
423
422
424
402
410
406
404
408
407
405
412
434
432
To Computer 312
430
436

FIG. 12

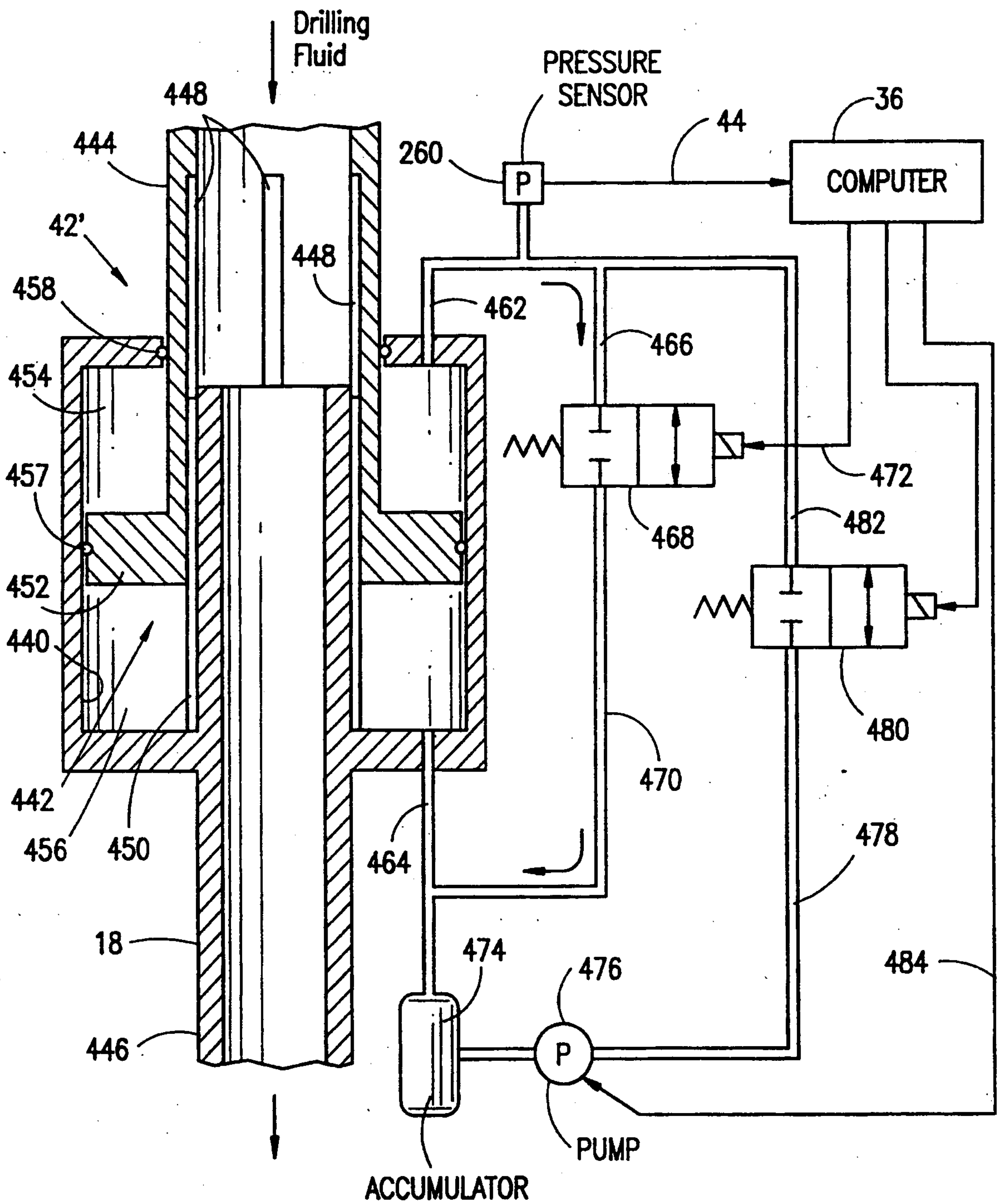
Drilling Fluid
PRESSURE SENSOR
COMPUTER
36
44
260
P
448
444
42'
448
458
462
466
454
472
457
468
482
452
480
440
470
442
456
450
464
478
18
474
476
484
446
P
PUMP
ACCUMULATOR

FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/21621

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01V 3/00; H04H 9/00
US CL :340/854.4, 853.1, 853.5; 367/82
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 340/854.4, 853.1, 853.2, 853.3, 853.5, 853.6; 367/82, 84, 86; 175/40

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS
hydraulic and (340/854.4 or 367/82)/ccls

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3,906,434 A (LAMEL et al.) 16 September 1975 (16/09/75), see entire document.	1, 31-32 and 34-35
X	US 4,314,365 (PETERSEN et al.) 02 February 1982 (02/02/82), see entire document.	1, 31 and 33-35
A	US 5,319,610 A (AIRHART) 07 June 1994 (07/06/94), see entire document.	8-30

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 DECEMBER 1998	26 JAN 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	SUNIL SINGH Diane Smith for
Facsimile No. (703) 305-3230	Telephone No. (703) 308-4024

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/21621

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

This application contains claims directed to more than one species of the generic invention. These species are deemed to lack Unity of Invention because they are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for more than one species to be searched, the appropriate additional search fees must be paid. The species are as follows:

Species I and II are drawn to Figures 1-9 and Figures 10-13 respectively.

The claims are deemed to correspond to the species listed above in the following manner:

Claims 2-7 and 32, and Claims 8-30 are drawn to Species I and II respectively

The following claims are generic: 1, 31 and 33-35

The species listed above do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, the species lack the same or corresponding special technical features for the following reasons: Species I varies stress by varying the speed of rotation of drill stem and Species II varies stress by varying axial movement of drill stem using a hydraulic means.

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